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February 2017

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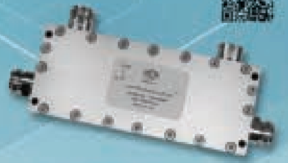

Low PIM Couplers

Low PIM Attenuators

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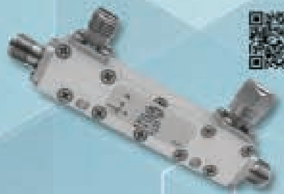
Power Divider/Combiner



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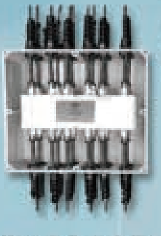

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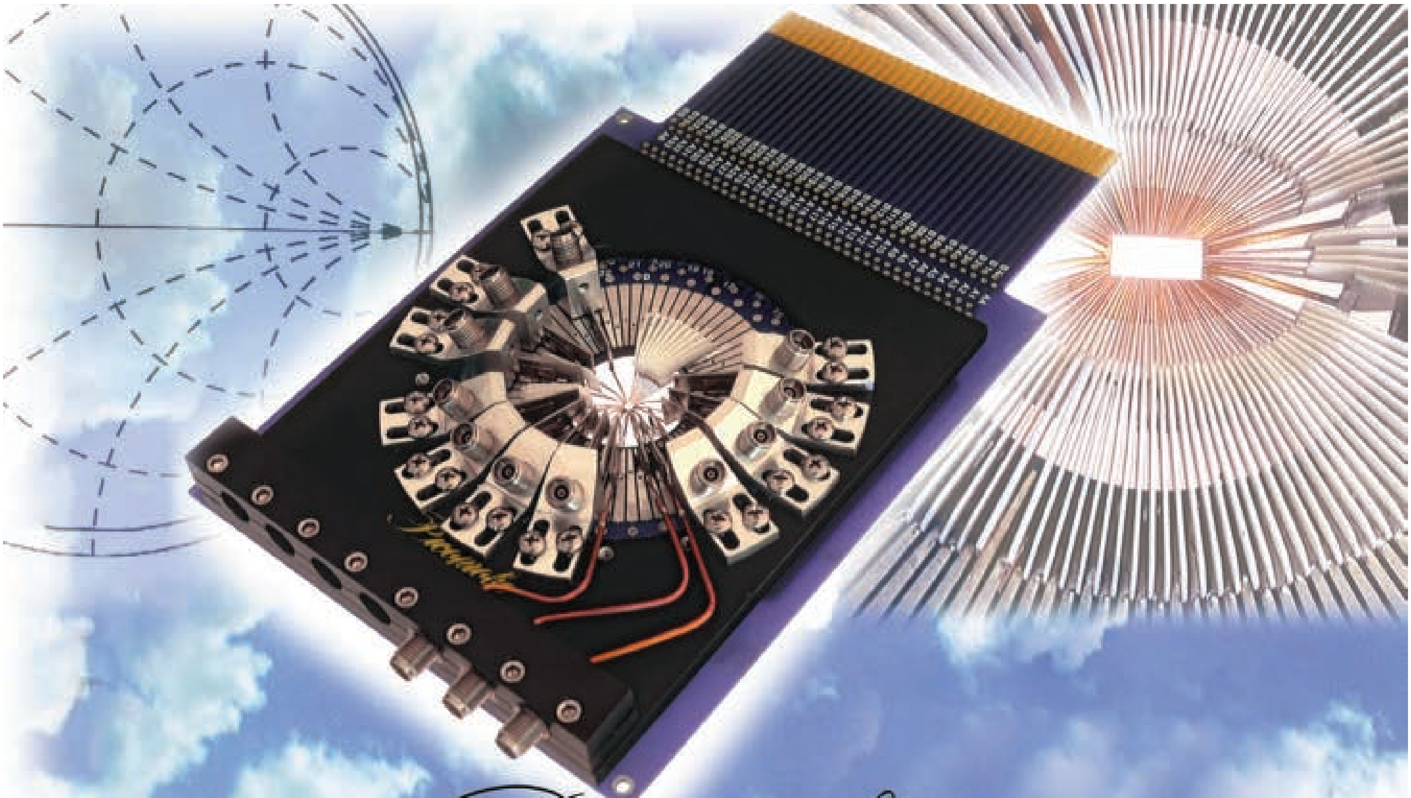

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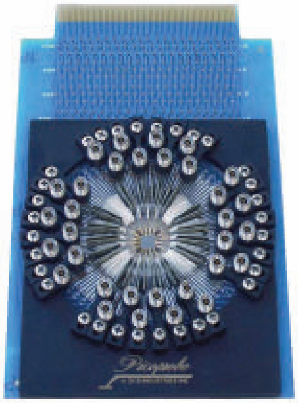

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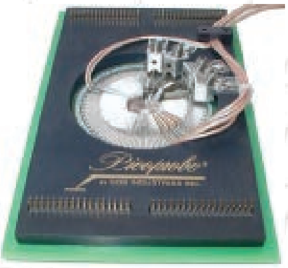

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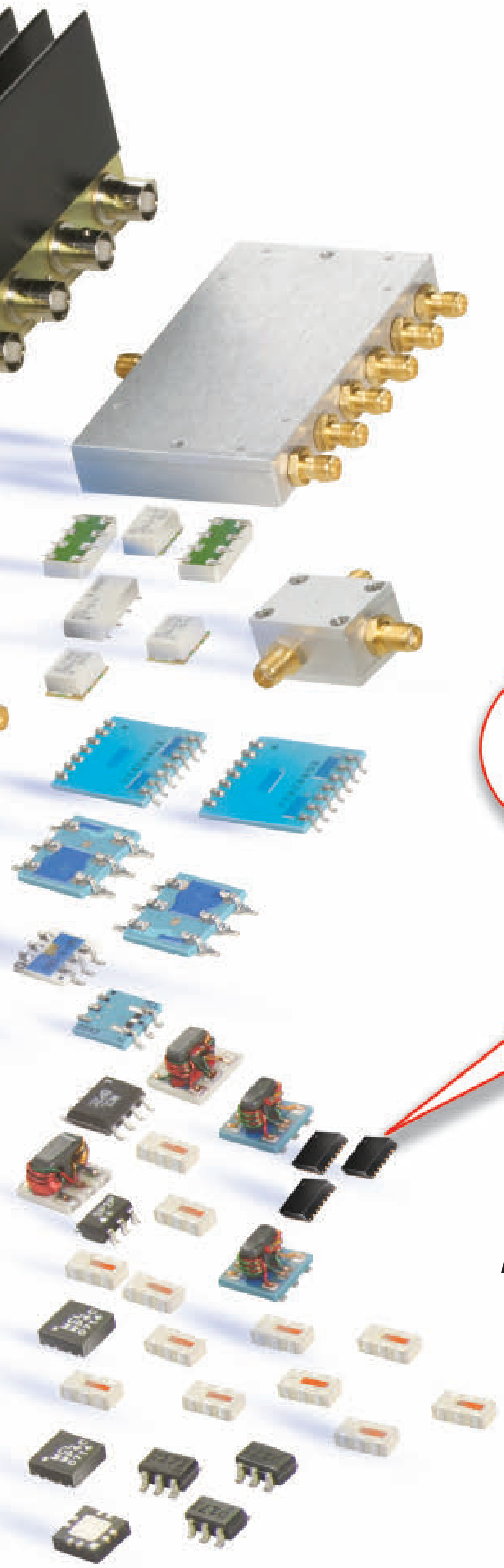

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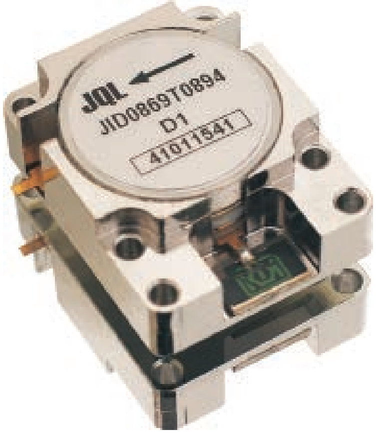

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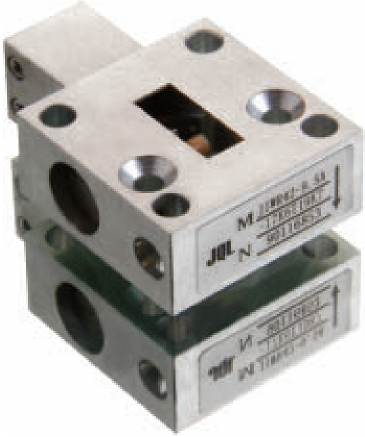
Cavity Filters

Surface Mount Circulators



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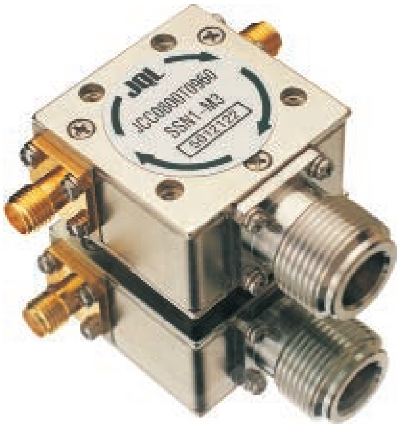
Power Combiners



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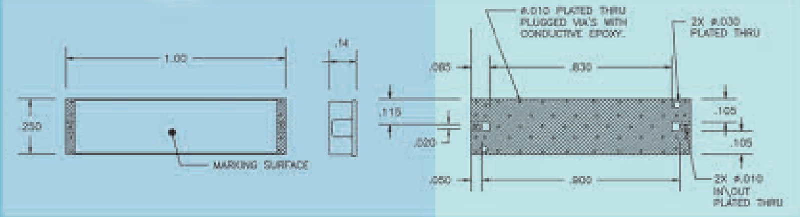

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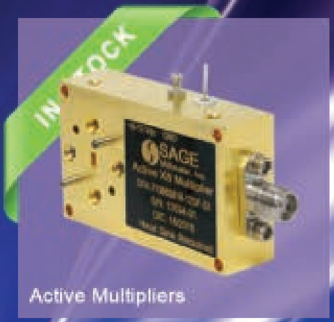

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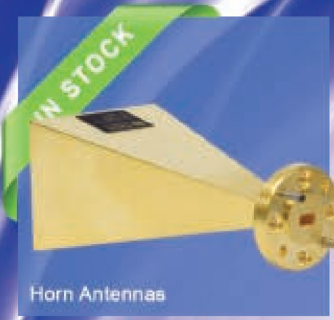
Faraday Isolators

Harmonic Mixers

Power Dividers



Horn Antennas

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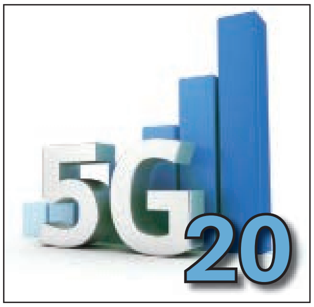

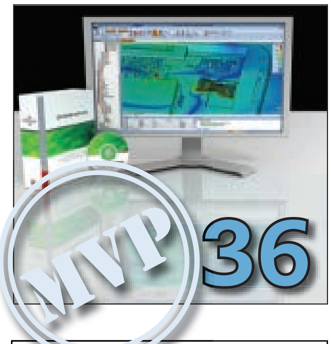

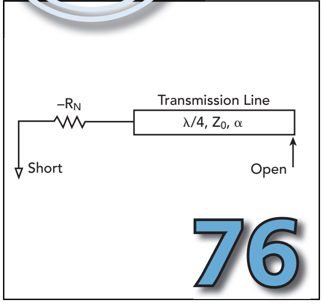

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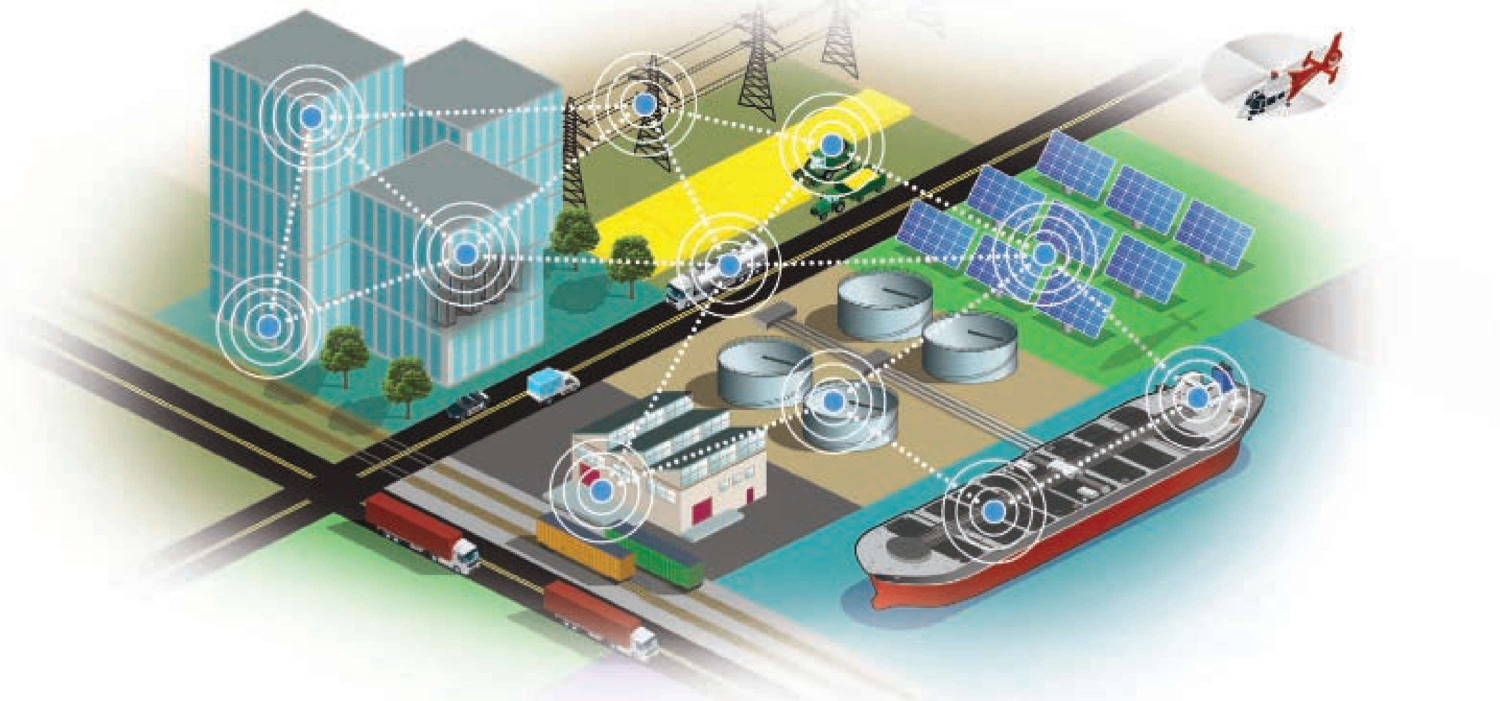

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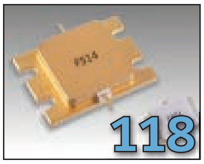

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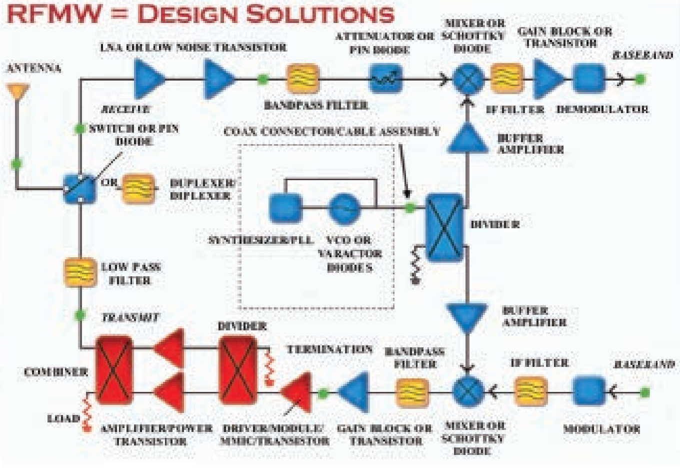

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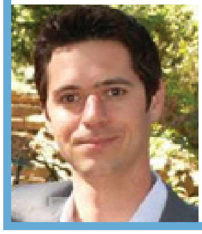

Christopher Marki, new CEO of **Marki Microwave**, discusses the product innovation that is taking the company far beyond its start, 25 years ago, as a high performance mixer supplier.

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December Survey

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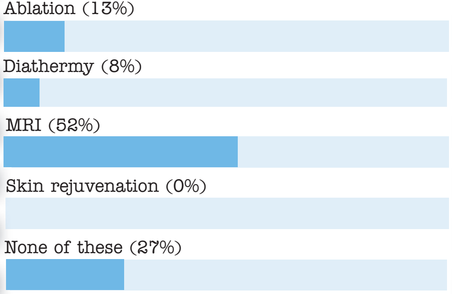

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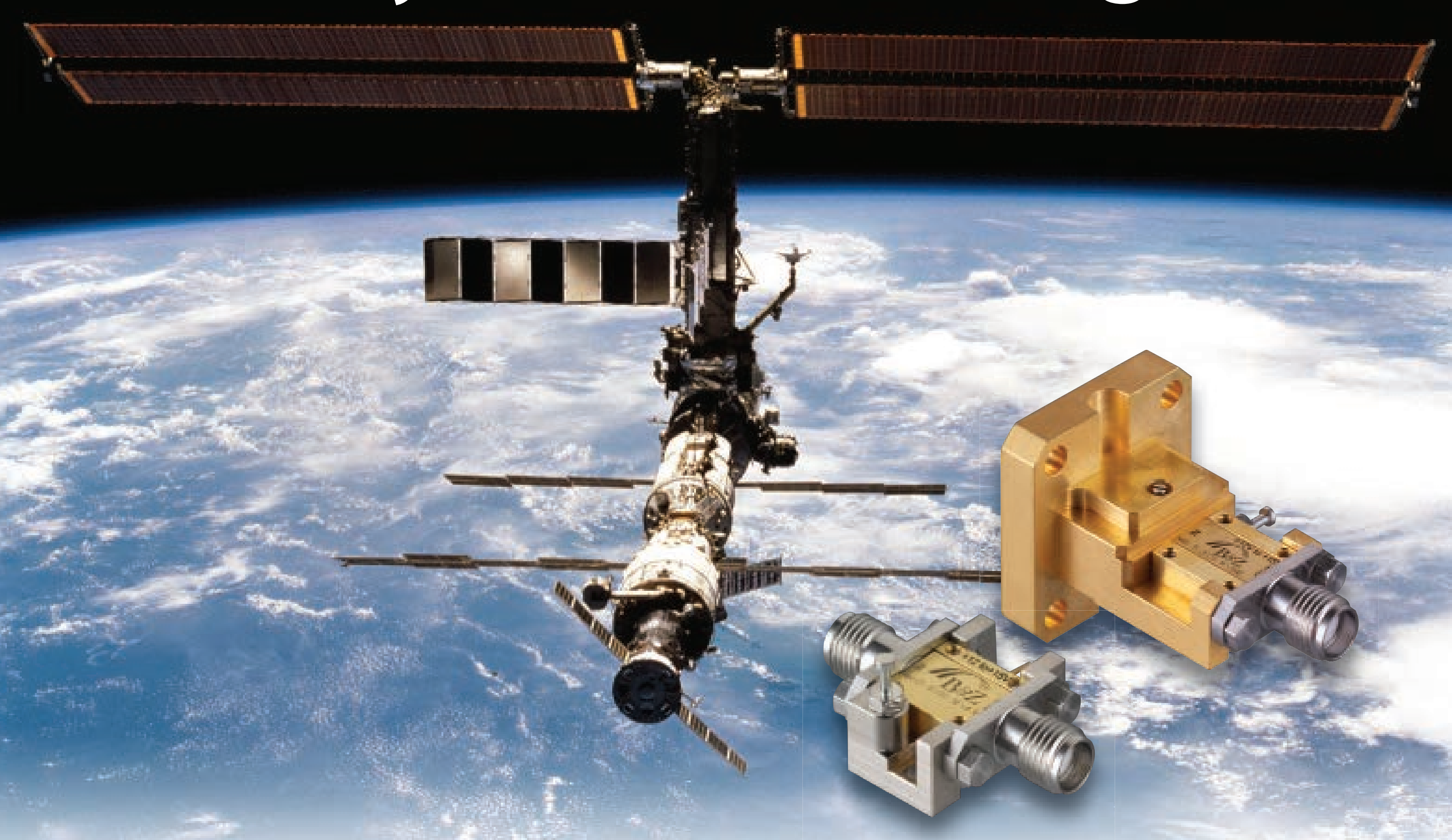

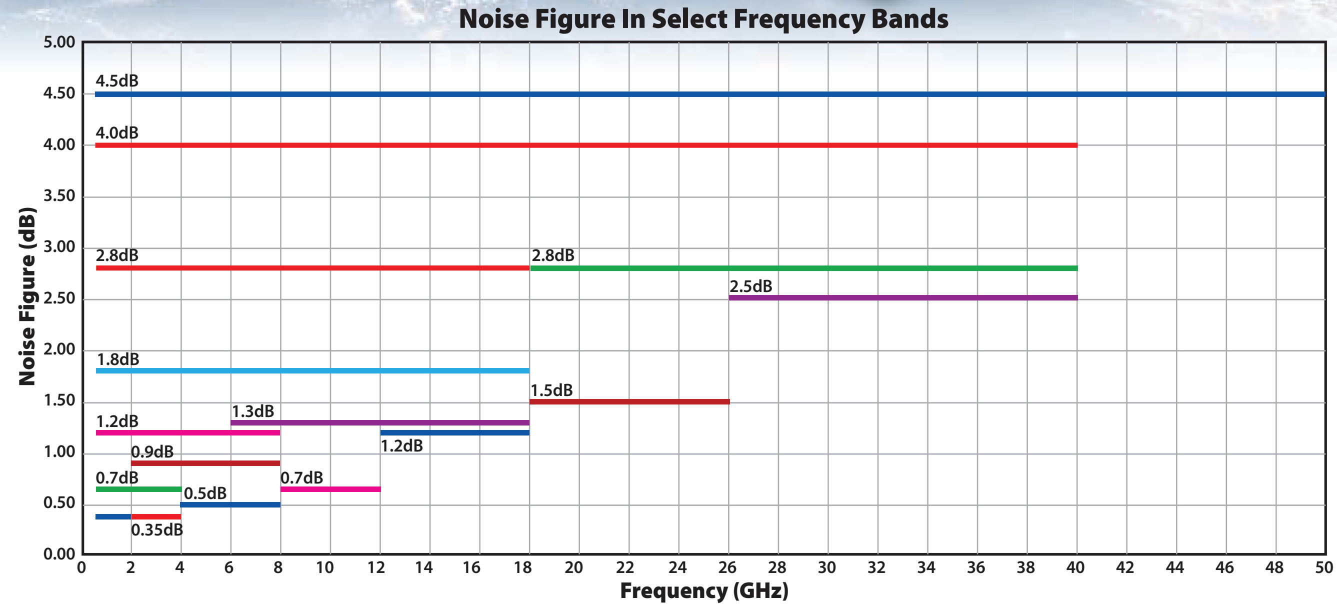
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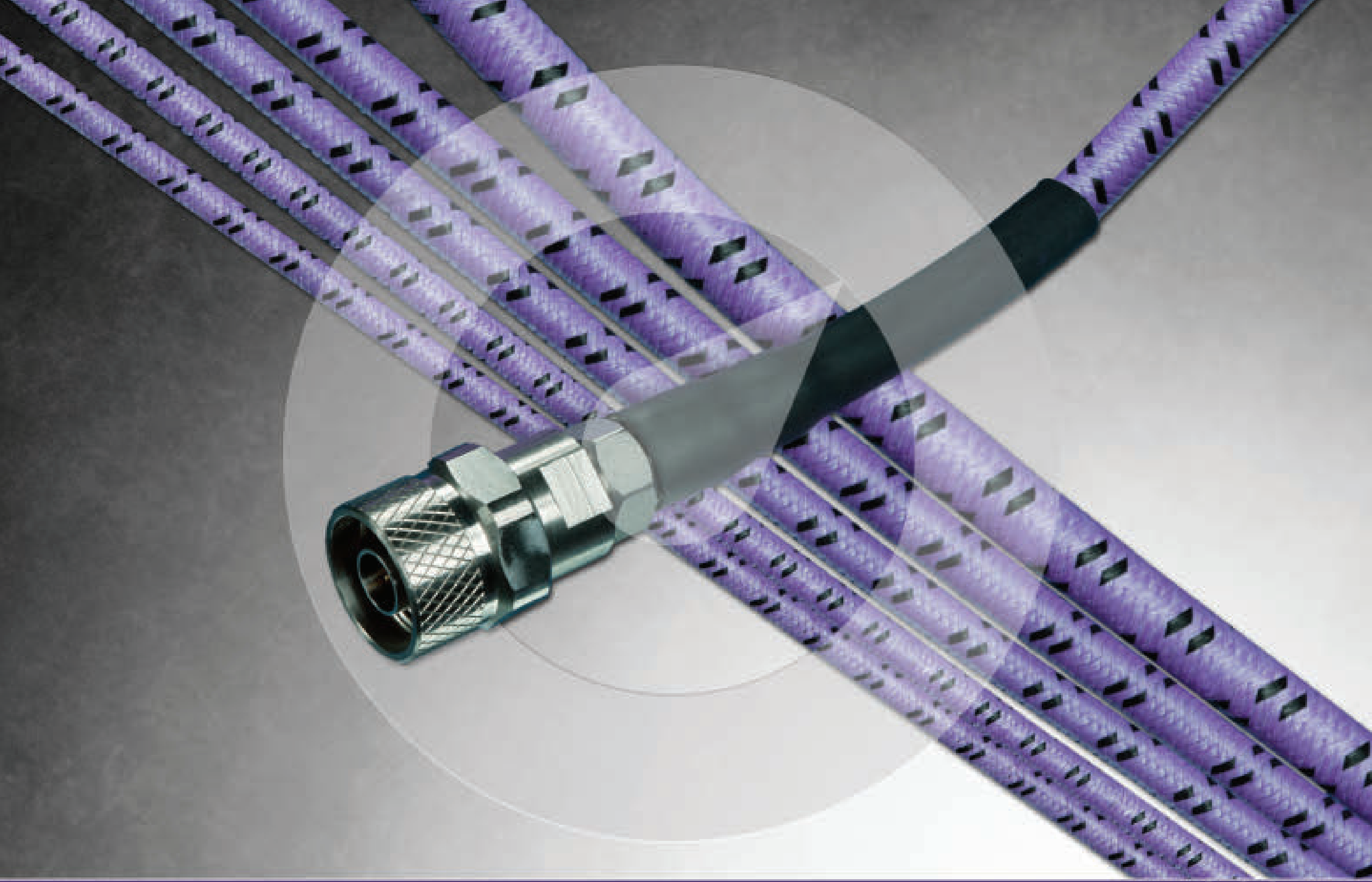

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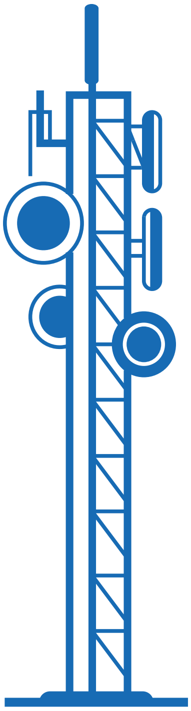

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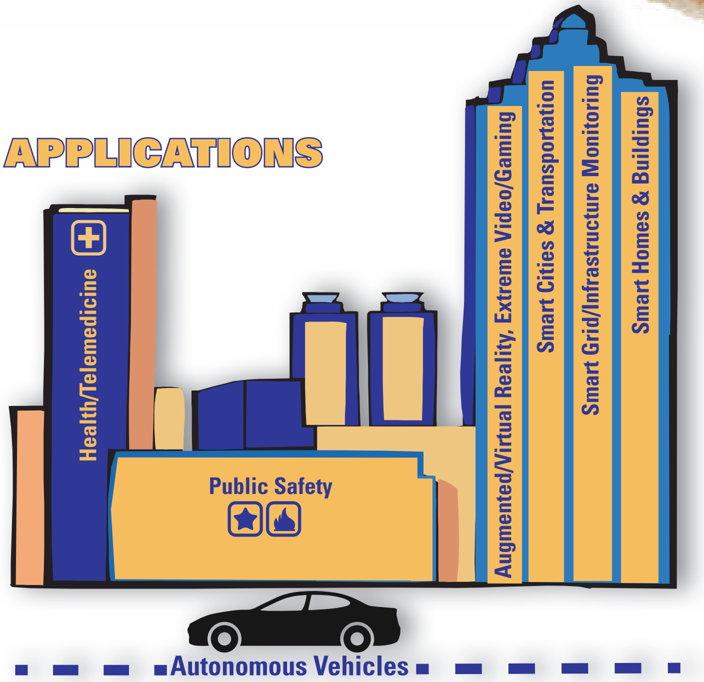

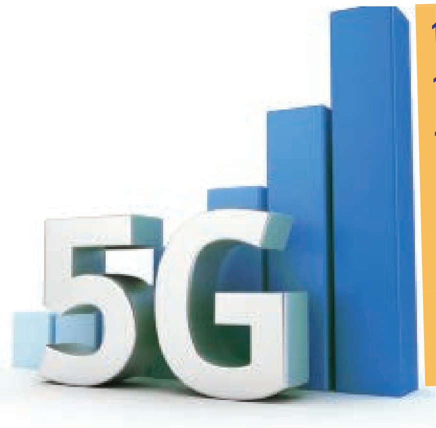

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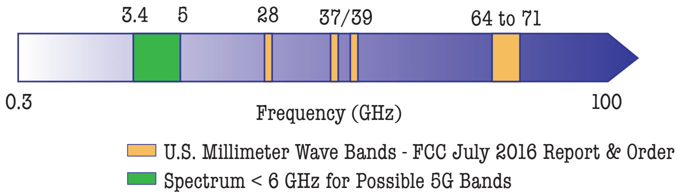

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GaN Powers Microwave Point-to-Point Radios

Kristoffer Andersson, David Gustafsson and Jonas Hansryd
Ericsson, Gothenburg, Sweden

Gallium arsenide (GaAs) has been the key technology enabler for high performance power amplifiers and receiver low noise amplifiers in the microwave frequency bands; however, the maturity of gallium nitride (GaN) technology provides an opportunity for substantial system level improvements. The high dielectric breakdown field of GaN results in higher voltage operation and hence higher power densities. With the help of GaN, the efficiency and the maximum output power of a microwave radio can be substantially increased — directly impacting the network cost of ownership. Today, GaN monolithic microwave integrated circuits (MMIC) are being introduced in commercial microwave radios.

Today there are as many mobile subscriptions as there are people in the world and the number of subscribers, which now includes machines and things, is rising at an increasing rate. High performance microwave radios have been key enablers in achieving the successful rollout of mobile networks. By 2020 it is expected that 65 percent of the radio base station sites (excluding China, Japan, Taiwan and South Korea) will be connected to a core network via a microwave radio.[1]

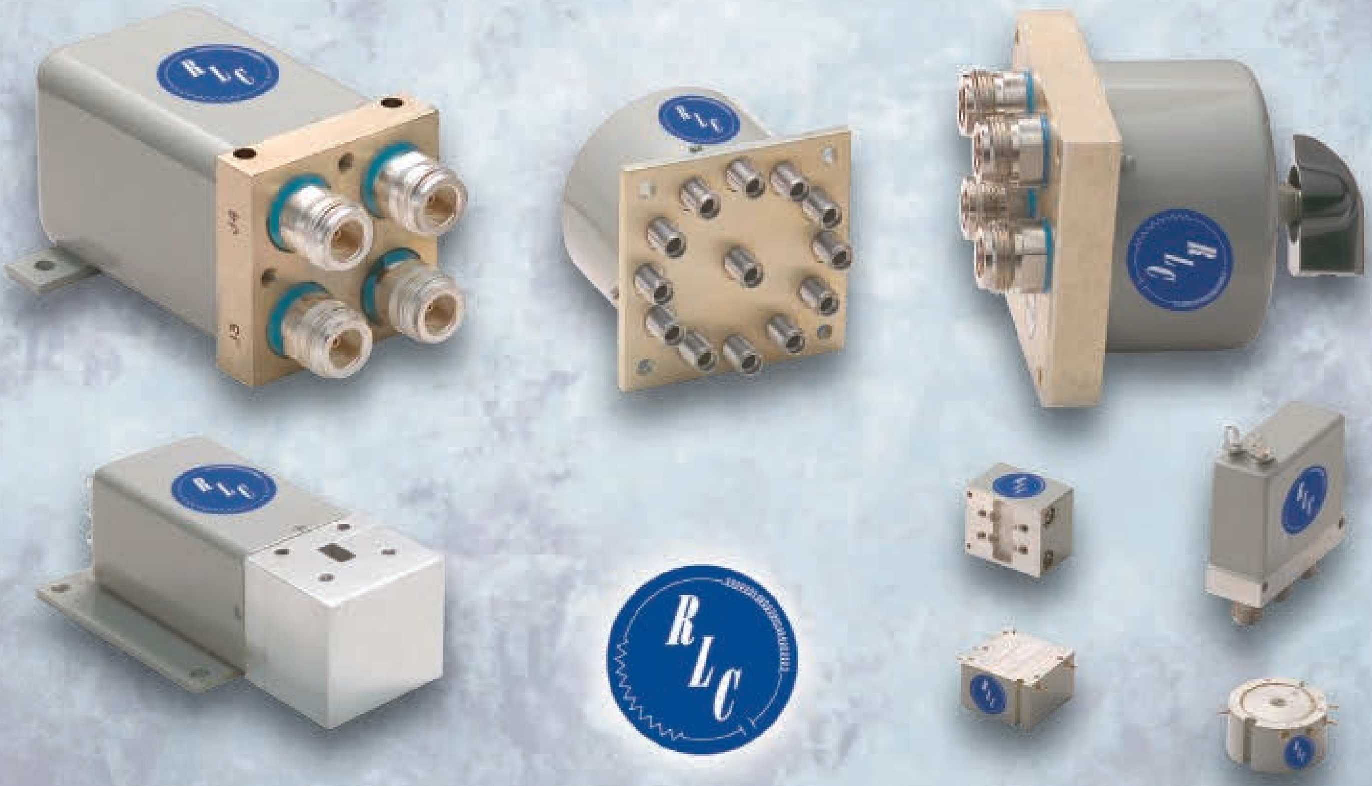
The major advantages of microwave radios are fast time-to-market and low cost of ownership. Two important parameters influencing cost of ownership are energy efficiency and system gain. Increasing the system gain allows for the use of smaller antennas while maintaining capacity and link availability. Cost of ownership is typically dominated by site rental which often represents 30 to 50 percent of the total cost.[2] A small antenna size results in a lower rental cost due to reduced wind loading of the mast. This also leaves room for additional radio links.

There are a number of components in the radio system enabling improved system performance such as high gain/high efficiency power amplifiers (PA), low noise receiver amplifiers (LNA) and error correction codes that regenerate incoming signals and mitigate disturbances such as interference, noise and spurious.

The available frequency bands for microwave radio span from 6 to 70/80 GHz with a total available bandwidth of about 40 GHz. For the traditional microwave bands (6 to 42 GHz), available channel bandwidths vary from a few MHz up to 112 MHz at the highest carrier frequencies. At 70/80 GHz, the channel bandwidth is wider than 1 GHz. To use the available spectrum in the most efficient way, modern radio systems often support modulation formats up to 4096-QAM. ***Figure 1*** shows the use of different frequency bands for microwave radio applications around the world. The most used bands are between 15 and 23 GHz.

GaN MMIC TECHNOLOGY

GaN comes with the distinct advantages of high output power density and high voltage operation. From a power amplifier perspective, GaN is a game changer. Using the same size transistors, it is possible to boost output power by at least four times compared to GaAs. Higher power density means less complex circuitry, hence higher efficiency and wider bandwidth. Several semiconductor companies now have access to GaN MMIC technology offering high performance processes with gate lengths less than 150 nm. This



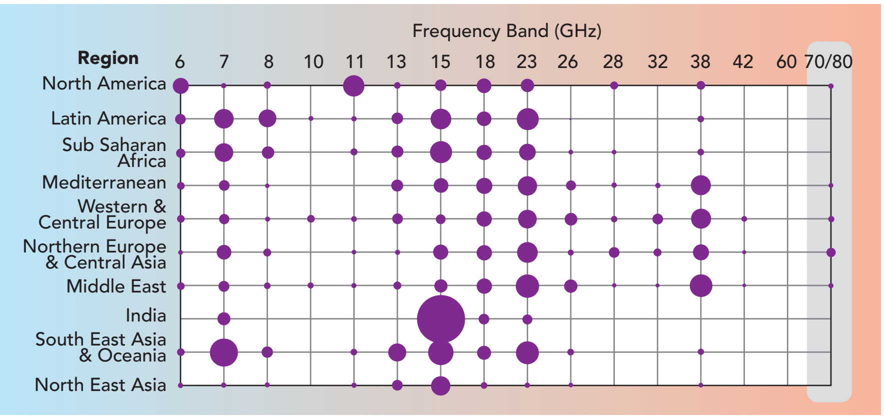


Fig. 1 Microwave radio market share vs. frequency band vs. geographic region.[3]

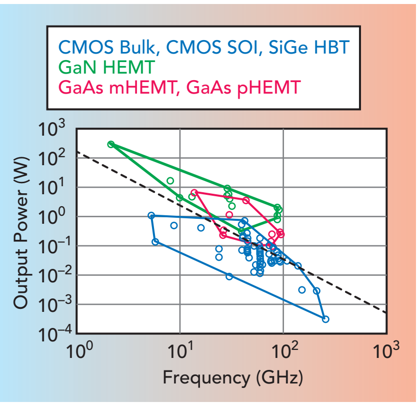


Fig. 2 Published power amplifier output power, reflecting capability of silicon, GaAs and GaN technologies.

enables high performance MMICs to greater than 40 GHz. ***Figure 2*** shows the potential of GaN power amplifiers compared to other semiconductor technologies. The figure shows regions of maximum output power versus frequency for published power amplifiers using three different semiconductor technologies (GaN, GaAs and silicon CMOS/SiGe). The dashed line shows a drop in power capability as a function of frequency for all technologies.

Existing barriers to wide-scale adoption of GaN technology in microwave point-to-point links is wafer pricing, packaging and memory effects due to trapping. The current generation of GaN MMICs is manufactured on semi-insulating silicon carbide (SiC) substrates. This technology provides the highest performance but not the most attractive price. Today the industry is moving to 6-inch SiC substrates, which helps push cost towards similar levels as GaAs. To further reduce cost, several companies are focusing on GaN-on-Silicon (GaN-on-Si) technology. GaN-on-Si is not as mature as GaN-on-SiC, however, and the performance will not be as high. One reason is the lower thermal conductivity of Si compared to SiC.

For telecommunication equipment, organic overmold packaging is the dominant technology due to its low cost and high reliability. However, only a very limited number of suppliers currently offer GaN MMICs with the necessary surface passivation to support organic overmold packaging.

Trapping in the GaN transistor may result in dynamic effects with slow time constants in the range of milliseconds to seconds.[19] The effects can appear as abrupt changes in small-signal gain following high output power events. This is more of an issue for radio base stations having very bursty traffic patterns than for microwave radio links where output power changes less rapidly.

MICROWAVE RADIO POWER AMPLIFIERS

A power amplifier is at maximum efficiency when operating at peak output power, while lowering the output power will significantly reduce efficiency. For linearity, the converse is true; the most linear operation is achieved at low output power. To mitigate the impairments associated with high efficiency operation, digital predistortion (DPD) techniques are used to compensate for power amplifier nonlinearities.

Power amplifiers for radio base stations are typically optimized for efficiency; power-added efficiencies as high as 50 to 70 percent are not uncommon. Linearity is then recovered using DPD techniques.

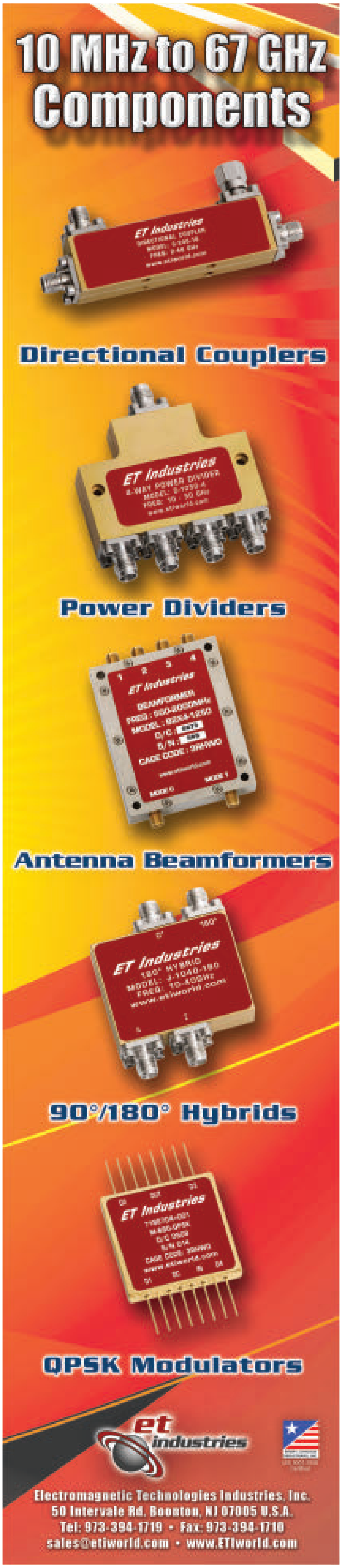


TABLE 1

TYPICAL PERFORMANCE OF PACKAGED GaAs CLASS AB POWER AMPLIFIERS

Reference	Frequency (GHz)	Saturated Output Power (dBm)	P_{1dB} (dBm)	Third Order Intercept Point (dBm)	Power-Added Efficiency for Linear Operation (%)	Supply Voltage (V)
4	7	35	34	43	5	6
5	23	33	31	38	3	6
6	38	28	27	38	< 2	4

TABLE 2

PERFORMANCE OF GaN DOHERTY POWER AMPLIFIERS ABOVE 6 GHz

Reference	Frequency (GHz)	Saturated Output Power (dBm)	Power-Added Efficiency for Linear Operation (%)	Supply Voltage (V)	Physical Configuration
9	7	36	31 - 39	28	Bare Die
11	7	35	35	20	Bare Die
14	7	38	36	28	Bare Die
17	7	42	21	28	Packaged
15	10	36	34	20	Bare Die
16	23	37	27	20	Bare Die

This focus on efficiency is motivated by the high output powers (100 W average) of these base station systems. Even a moderate increase in power-added efficiency leads to a significant reduction in power consumption and cooling requirements.

Power amplifiers in microwave radios for point-to-point communications are operated Class AB to support high order modulation schemes (up to 4096-QAM). If a DPD system is available, it is typically used to enable high order modulation rather than for boosting efficiency. The maximum saturated output power for a GaAs MMIC amplifier is about 40 dBm up to 10 GHz, falling to about 26 dBm at 86 GHz (E-Band). The associated maximum efficiency is about 35 percent up to 10 GHz and about 15 percent at 86 GHz. For linear operation (i.e. 10 dB from saturation), these efficiencies drop rapidly to below 10% (3% to 10% depending on frequency). These power levels represent what is possible to achieve in a commercial setting. Striving for higher output power increases cost and power consumption.

For most point-to-point frequency bands, there are a number of organic packaged GaAs MMIC power amplifiers. For the lower frequencies, saturated output power typically lies in the range of 2 to 4 W and the power-added efficiency for linear operation is slightly less than 5 percent. ***Table 1*** shows the typical performance of commercially available packaged GaAs Class AB power amplifiers. Taken from vendor datasheets, it serves as an illustration of the current state for point-to-point amplifiers: linear operation at the expense of efficiency.

Efficient Point-to-Point Communications Power Amplifiers

Wireless radio base stations have for some time been equipped with Doherty power amplifiers that provide high efficiency in both saturation and in back-off.[7,8] In its most basic form, the Doherty amplifier improves efficiency in back-off by using two parallel amplifier branches: a carrier amplifier and a peaking amplifier. The carrier amplifier is connected to the peaking amplifier via an impedance inverter and the peaking amplifier is then connected

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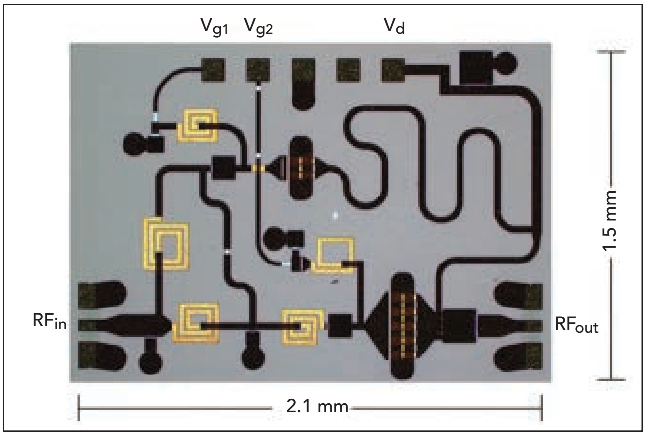
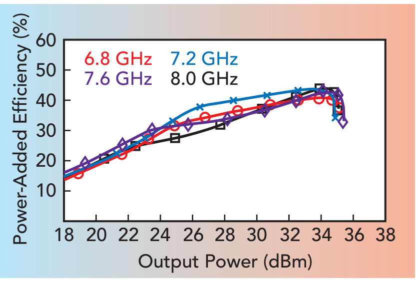


▲ **Fig. 3** **7 GHz GaN MMIC Doherty amplifier.**[11]

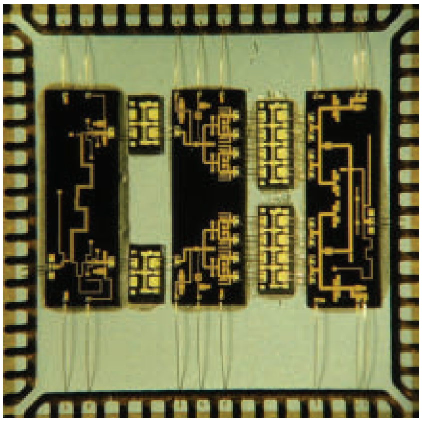
to the load. This arrangement at low power presents a high impedance to the carrier amplifier, which decreases as the power increases. This load modulation ensures that the carrier amplifier operates near saturation (and hence at high efficiency) over a wide range of output powers—typically 6 dB or more. Although the theoretical Doherty amplifier is a linear amplifier, the practical realization is inevitably very nonlinear. Hence, the radio base station is also equipped with a digital predistortion system that provides linear operation.

Given the success of the Doherty amplifier in the radio base station market, there have been attempts to carry over the Doherty technology to the point-to-point segment. The principal circuit level challenges have been the shorter wavelengths in the point-to-point communication bands and the low power density of GaAs. Shorter wavelengths necessitate an integrated solution in contrast to the sub-6 GHz Doherty amplifiers, where the combiner and splitting networks are implemented on the amplifier printed circuit board. The low power density of GaAs puts a limit on the maximum output that can be achieved. With the advent of short gate length GaN MMIC technology, it is finally possible to realize Doherty power amplifiers beyond 6 GHz, delivering more than 10 W in saturation.

Recent work with GaN Doherty power amplifiers operating primarily in the 7 GHz bands[9-15] and at 23 GHz[16] show that state-of-the-art GaN technology is capable of achieving a power-added efficiency of 30 percent (with 8 to 9 dB back-off) and more than 20 W of saturated output power (see ***Table 2***). In 2012, Gustafsson et al.,[11] demonstrated the performance of a GaN MMIC Doherty power amplifier operating in a microwave radio band (see ***Figure 3***). ***Figure 4*** shows its efficiency. Using a DPD system, the amplifier achieved an average efficiency of greater than 35 percent while keeping its adjacent channel leakage power ratio (ACLR) below -48 dB for a 10 MHz 256-QAM signal.

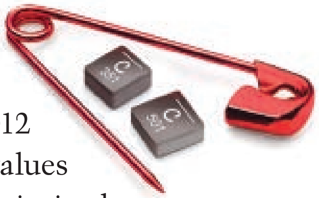


▲ **Fig. 4** **Power-added efficiency of 7 GHz GaN MMIC Doherty amplifier.**[11]



▲ **Fig. 5** **GaN hybrid power amplifier before overmold application.**[17] **The power transistors are GaN HEMTs, and the passive input, interstage and output networks are fabricated in GaAs.**

More recently, Gustafsson et al.,[17] demonstrated the performance of a GaN hybrid Doherty amplifier. The hybrid approach with passive GaAs for matching circuits limits the GaN content, which has the potential to lower the cost of the Doherty amplifier. The two-stage hybrid amplifier consists of an integrated passive GaAs input, interstage and



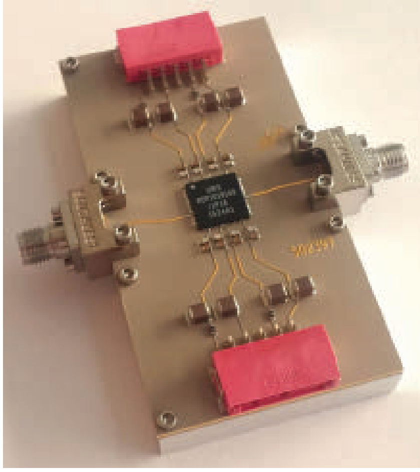


Fig. 6 Packaged GaN hybrid power amplifier mounted to an evaluation board.[17]

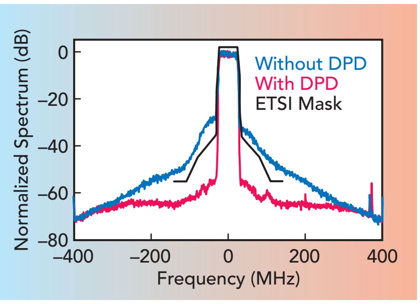


Fig. 7 Measured output spectrum of a GaN hybrid power amplifier, with and without DPD, driven by a 50 MHz, 4096-QAM input at 6.65 GHz.[17]

output matching circuits and GaN power bars for the amplifier stages. ***Figures 5*** and ***6*** show the inside of the package and the packaged amplifier, respectively. Using a DPD system, the amplifier delivered 34 dBm average output power with a 50 MHz 4096-QAM signal at an average power-added efficiency of 20 percent, while fulfilling Class 8B ETSI spectral requirements[18] (see ***Figure 7***). Linearization was performed using direct learning table DPD (24 tables, 16 bins) with least square estimation of the table coefficients.

This demonstration shows that GaN and Doherty operation can increase the efficiency well beyond what is achievable in GaAs. As previously mentioned, the Doherty amplifier must be augmented with DPD. The wide bandwidth of point-to-point channels—up to 112 MHz for the traditional microwave bands—puts tough requirements on the digital predistortion system. To compensate for seventh-order nonlinearities, digital-to-analog converters should run with at least 7x oversampling (i.e., > 784 MHz). The same goes for the analog-to-digital converter in the local observation receiver (>784 MSPS). In addition to high data rates, vertical resolution should be high enough to support very high modulation rates (i.e., 4096-QAM). These data converters have been historically power hungry and, thus, the efficiency of the whole radio system is compromised. By using state-of-the-art data converters, however, it is now feasible to design digital predistortion systems with low enough power consumption.

The Promise of GaN PAs in Microwave Point-to-Point Radios

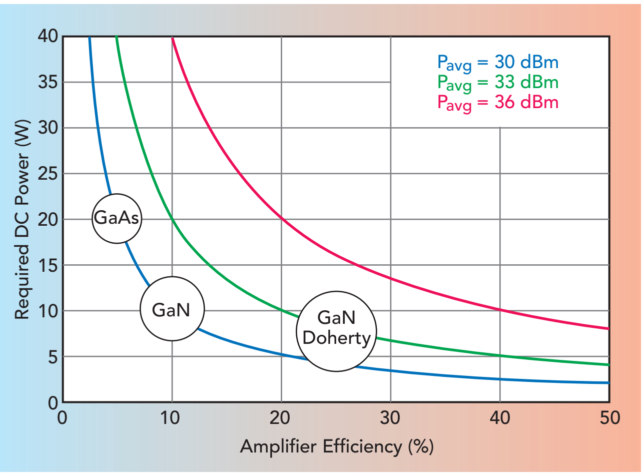


Fig. 8 DC power consumption vs. amplifier efficiency and average output power. Circled regions show typical performance of GaAs Class AB, GaN Class AB and GaN Doherty power amplifiers.

There are two main uses for GaN in commercial microwave radios. The first is to leverage power density to increase output power and, thus, system gain. Using short gate length GaN MMIC processes (e.g., 0.15 μm), it is possible to substantially increase output power, compared to GaAs, up to at least 23 GHz. This comes at the cost of increased power consumption, as amplifier efficiencies are expected to improve marginally. The other use is to improve

efficiency by introducing high efficiency power amplifier architectures (e.g., Doherty). With a high efficiency amplifier, it is possible to increase output power while also decreasing power consumption. Furthermore, the thermal footprint of the amplifier is reduced, enabling simpler cooling solutions.

Figure 8 shows the required DC power as a function of power amplifier efficiency for three different average power levels (30, 33 and 36 dBm). The circled areas indicate typical performance regions for GaAs Class AB, GaN Class AB and GaN Doherty power amplifiers. By replacing GaAs with GaN, an incremental increase in efficiency is achieved. At these relatively low efficiencies, however, even an incremental increase leads to substantial power savings. An increase from 5 to 10 percent power-added efficiency can reduce power consumption by 10 W and, hence, lower the total cost of ownership. The use of GaN Doherty power amplifiers enables power-added efficiencies in the range of 25 percent. This not only decreases power consumption but also increases system gain and output power.

Looking at GaN opportunities in terms of carrier frequency, there are two distinct regions (see ***Figure 9***). The first is at lower frequencies (up to about 13 GHz), where efficient Doherty operation has been demonstrated. Here one can take advantage of increased efficiency and reduced energy consumption or increased output power without increased power consumption or an enlarged thermal footprint. This region utilizes the full potential of GaN technology. The gray area indicates a transition region between Doherty and Class AB power amplifiers; which technology is best to use depends on the efficiencies that can be achieved from Doherty amplifiers above 15 GHz. For the higher frequency bands (18 GHz and above), it is now possible to replace existing GaAs power amplifiers with high power GaN versions to increase output power.

CONCLUSION

GaN technology is now being introduced in commercial microwave radios. While the first wave of products provides only an incremental reduction in power consumption, Doherty amplifiers at microwave frequencies enabled by GaN and high performance data conversion technology will, in the coming

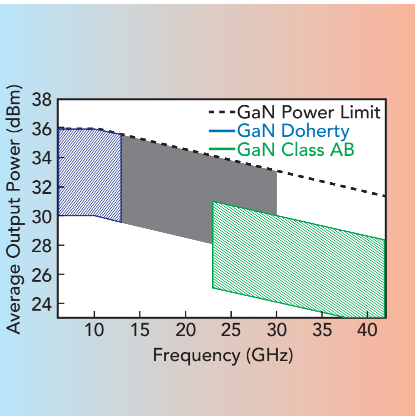


Fig. 9 Operating regions for Doherty and Class AB GaN power amplifiers.

years, provide power and efficiency improvements, just as they have for the base station market. ■

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EM simulation reduces costs and design time, enabling users to analyze and improve the performance and compliance of components and systems from the earliest stages of design. CST STUDIO SUITE® 2017, the upcoming* release of the EM and multiphysics simulation package, introduces new features that extend the software's range of applications. These features include both front-end and back-end improvements across the suite, with many focusing on tools for synthesizing and simulating components, as well as for managing and analyzing these components as systems.

FILTER DESIGNER 3D

Cross-coupled filters offer a compact and high-performance way to use the spectrum efficiently. However, the complex and sensitive nature of these filters makes them challenging to design with traditional methods. Filter Designer 3D can automatically synthesize cross-coupled and diplexer filter designs to meet the specifications, including transmission zeroes, Q-factor and equiripple. Filter Designer 3D can calculate the coupling matrix on which the filter engineer can base a design, or produce a full filter model that can be used as the basis of an optimization or system simulation using the full-wave 3D solvers of CST STUDIO SUITE. An example is shown in ***Figure 1***.

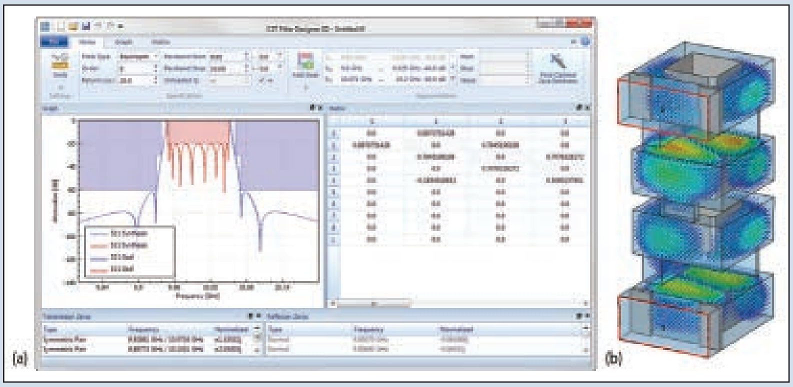
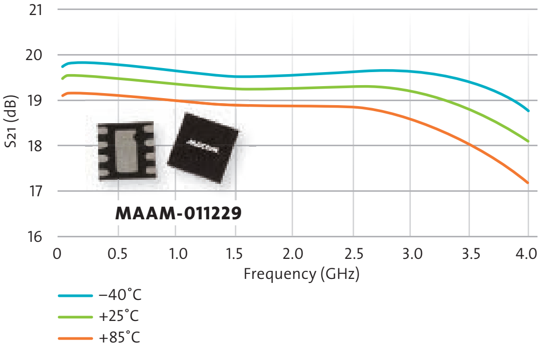


***Fig. 1** Multimode cavity filter design using Filter Designer 3D (a) and field plot (b).*

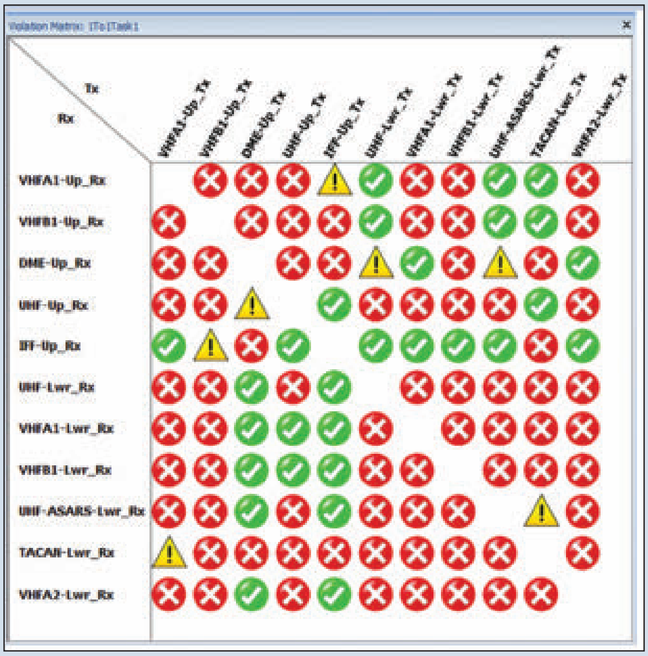
ANTENNA-TO-ANTENNA COUPLING

System integrators and electromagnetic compatibility (EMC) engineers often need to know how antennas on a shared platform couple to each other. On smaller platforms, the CST® Time Domain Solver and Integral Equation Solver are efficient options for antenna coupling simulation. CST STUDIO SUITE 2017 expands this capability to extremely large platforms as well. The ray-tracing Asymptotic Solver (A Solver) in CST STUDIO SUITE can now directly calculate the coupling between antennas. The A Solver can simulate extremely large platforms such as aircraft, ships and buildings very efficiently, making it well suited to many kinds of antenna placement scenarios.


21
20
19
18
17
16
S21 (dB)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Frequency (GHz)
MAAM-011229
−40˚C
+25˚C
+85˚C

INTERFERENCE TASK

Electromagnetic interference between subsystems, such as antennas on a platform or channels on a PCB, is a vital consideration in many applications. The new Interference Task, illustrated in ***Figure 2***, offers a straightforward approach for investigating potential EMI issues using coupling data from simulations—including results from the new A Solver approach. With the Interference Task, EMI problems can be identified and mitigation approaches tested on a virtual prototype.



Violation Matrix: ITs ITask1

Tx Rx	VHFA1-Up_Tx	VHFB1-Up_Tx	DME-Up_Tx	UHF-Up_Tx	IFF-Up_Tx	UHF-Lwr_Tx	VHFA1-Lwr_Tx	VHFB1-Lwr_Tx	UHF-ASARS-Lwr_Tx	TACAN-Lwr_Tx	VHFA2-Lwr_Tx
VHFA1-Up_Rx		✗	✗	✗	⚠	✓	✗	✗	✓	✓	✗
VHFB1-Up_Rx	✗		✗	✗	✗	✓	✗	✗	✓	✓	✗
DME-Up_Rx	✗	✗		✗	✗	⚠	✓	✗	⚠	✗	✓
UHF-Up_Rx	✗	✗	⚠		✓	✗	✗	✗	✗	✓	✗
IFF-Up_Rx	✓	⚠	✗	✓		✓	✓	✓	✓	✗	✓
UHF-Lwr_Rx	✗	✗	✓	✗	✓		✗	✗	✗	✗	✗
VHFA1-Lwr_Rx	✗	✗	✓	✓	✓	✗		✗	✗	✗	✗
VHFB1-Lwr_Rx	✗	✗	✓	✓	✓	✗	✗		✗	✗	✗
UHF-ASARS-Lwr_Rx	✗	✗	✓	✗	✓	✗	✗	✗		⚠	✗
TACAN-Lwr_Rx	⚠	✗	✗	✗	✗	✗	✗	✗	✗		✗
VHFA2-Lwr_Rx	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	

▲ ***Fig. 2** The Interference Task shows which combinations of RF systems can lead to co-site interference.*

CHT SOLVER FOR ELECTRONICS COOLING

Thermal effects are critical in high-power or high-speed applications—overheating can cause thermal expansion, detuning and potentially damage the device. Simulating these effects accurately needs multiphysics simulation, with EM and thermal solvers linked together. CST STUDIO SUITE 2017 sees the company expand its multiphysics tools with the Conjugate Heat Transfer (CHT) Solver. This uses computational fluid dynamics (CFD) to simulate the flow of air through devices, taking fans and vents into account. With the CHT Solver, users can include the cooling systems in their multiphysics simulation, allowing these systems to be designed and optimized before constructing prototypes.

3D COMPONENT LIBRARY

Many companies have built up a collection of simulation models and components that can be combined and modified to create new products. The Component Library in CST STUDIO SUITE 2017 offers a straightforward way to store, manage and find these models.

Component models can be loaded into the library and archived with tags and version control. These can then be searched and downloaded to be integrated into new simulation projects, speeding up the early stages of design. Users can create both public and private libraries and models can be encrypted, allowing users to ensure that sensitive designs remain confidential.

CHIP INTERFACE

As speeds increase, the design of integrated circuits (IC) is increasingly becoming a task that requires full-wave 3D simulation. This is especially true of RFIC components such as inductors. The CST STUDIO SUITE 2017 chip interface allows IC designs to be imported in Open Access Database and GDSII format, and simulates the fabrication process of ICs, layer by layer, to produce a realistic 3D model of the IC suitable for simulation.

ARRAY IMPROVEMENTS

The Array Wizard is a well-established part of CST STUDIO SUITE, and automatically guides users through the array design workflow, from simulation of the individual element to automatic construction of the entire array. The 2017 version will add support for non-periodic and arbitrary 3D arrays, broadening the use cases for the tool significantly.

* CST STUDIO SUITE 2017 is due for release at the end of Q1 2017.

VENDOR**VIEW**

Computer Simulation Technology (CST)
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Evolution of the Smartphone

Todd Gillenwater, Mobile Devices CTO and VP of Engineering
Qorvo, Greensboro, N.C.

In less than 10 years, mobile phones have evolved from tools used mostly for talking and texting to highly complex, sophisticated devices that are central to almost every aspect of our lives. They have changed the way we communicate, letting us share experiences in real time by uploading and downloading live video. They guide us while driving, making paper maps almost obsolete. They have become universal controllers for Internet of Things (IoT) devices ranging from home thermostats to hotel room door locks. And they have enabled companies to create entire new cloud-based business models. Ride-sharing companies like Uber rely on the ubiquity of mobile devices that let users find and pay for rides that are automatically directed to their locations.

All of these applications mean that high speed, highly reliable data connections are essential to everyone's daily life. Demand for mobile data continues to grow rapidly: the November 2016 Ericsson Mobility Report predicts that global smartphone subscriptions will rise from 3.3 billion in 2015 to 6.8 billion in 2022, with the data used per smartphone expected to rise nearly 8x to 11 GB/month over the same period. Trends such as virtual reality and real-time video require high performance networks that provide low latency as well as higher data rates.

To handle the growth in mobile data, successive network generations—2G, 3G, 4G (LTE) and, in the future, 5G—have used a variety of methods to progressively increase network capacity and data rates. One way is allocating many more frequency bands. A flagship LTE smartphone designed for global use may support more than 30 bands today, compared with fewer than 10 in 2010. The trend is continuing, as regulators allocate new higher frequency bands at 3.5 GHz and above and refarm existing spectrum, such as the 600 MHz band previously used for TV broadcasting. Channel bandwidth has increased, from 200 kHz with 2G to 20 MHz with 4G, even more using carrier aggregation (CA) in LTE Advanced (see ***Figure 1***). This is being combined with techniques for producing higher data rates and capacity from a given bandwidth, such as MIMO, more complex modulation and network densification, including the use of small cells.

Today, key trends include LTE Advanced, which network operators are now deploying, and its successor LTE Advanced Pro (defined in 3GPP Release 13 and later releases). These LTE network enhancements ensure that 4G will continue to play an important role even after 5G begins to be deployed. LTE will operate in parallel with 5G and provide adequate performance for many applications. LTE Advanced introduced CA, which aggregates the bandwidth of up to five RF carriers, called component carriers (CC). LTE Advanced allows maximum network data rates up to 1 Gbps, and LTE Advanced Pro will increase the possible number of CCs to 32, allowing up to 3 Gbps. Wi-Fi is becoming more important with the introduction in LTE Advanced Pro of licensed assisted access (LAA), which uses CA to combine licensed LTE spectrum with unlicensed Wi-Fi spectrum at 5 GHz to achieve greater data rates.

SMARTPHONE TRENDS AND CHALLENGES

As smartphone data performance requirements continue to grow, so does the complexity of the RF front-end, creating a series of new challenges for the engineers working on smartphone designs. Today's requirements are creating design challenges that include maximizing linearity and isolation, managing power consumption and antenna tuning. Greater integration is required, since an increasing number of bands must squeeze into the limited space allocated to the RF front-end. Another important trend is the emergence of smartphone market tiers, each with differing RF requirements. This article discusses each of these and how the smartphone will evolve to handle 5G.

Isolation

The requirement to accommodate more LTE bands within the RF front-end creates challenges

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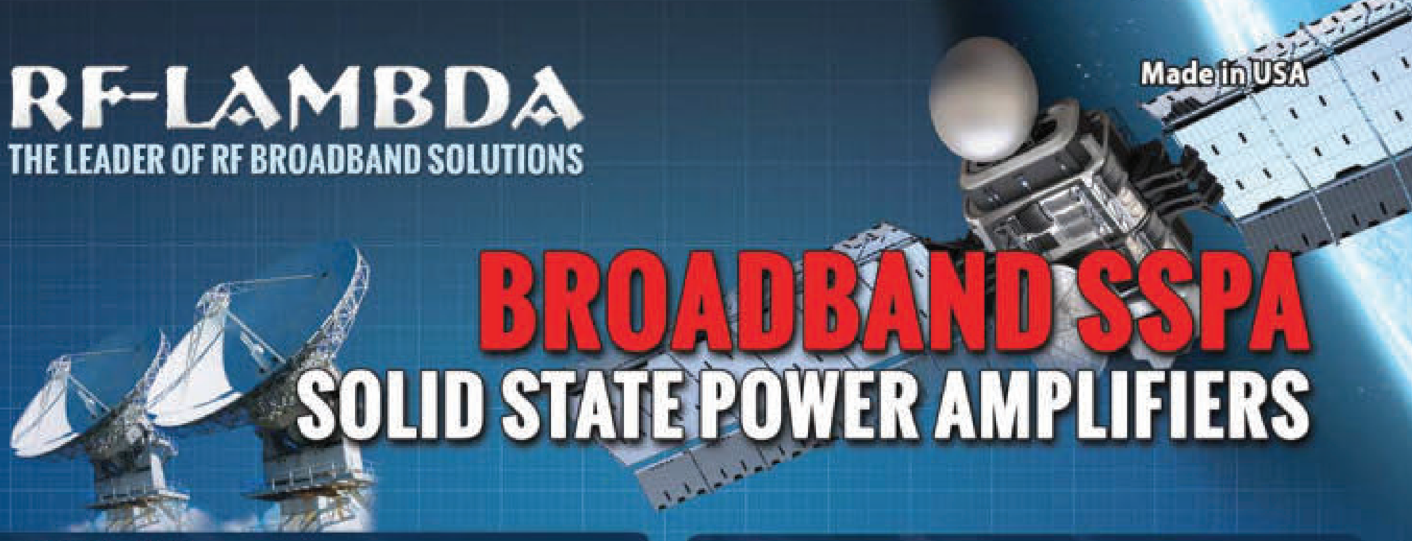

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RFLUPA02G06GC
100W 2-6GHZ

6-18GHZ C, X, KU BAND

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50W 8-11GHZ

RFLUPA0618GC
25W 6-18GHZ

RFLUPA06G12GB
25W 6-12GHZ

18-50GHZ K, KA, V BAND

RFLUPA18G47GC
2W 18-47GHZ

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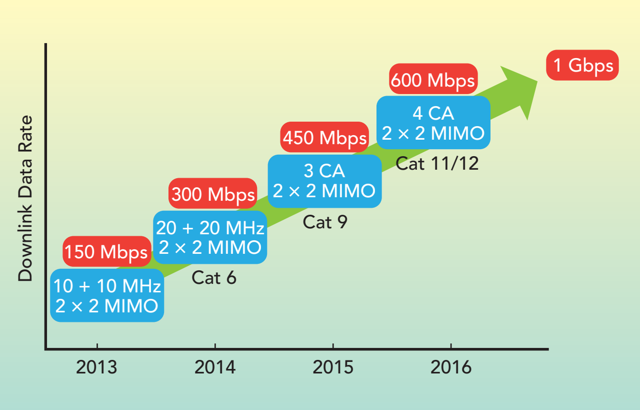


Fig. 1 Increasing downlink data rate enabled by carrier aggregation.

TABLE 1

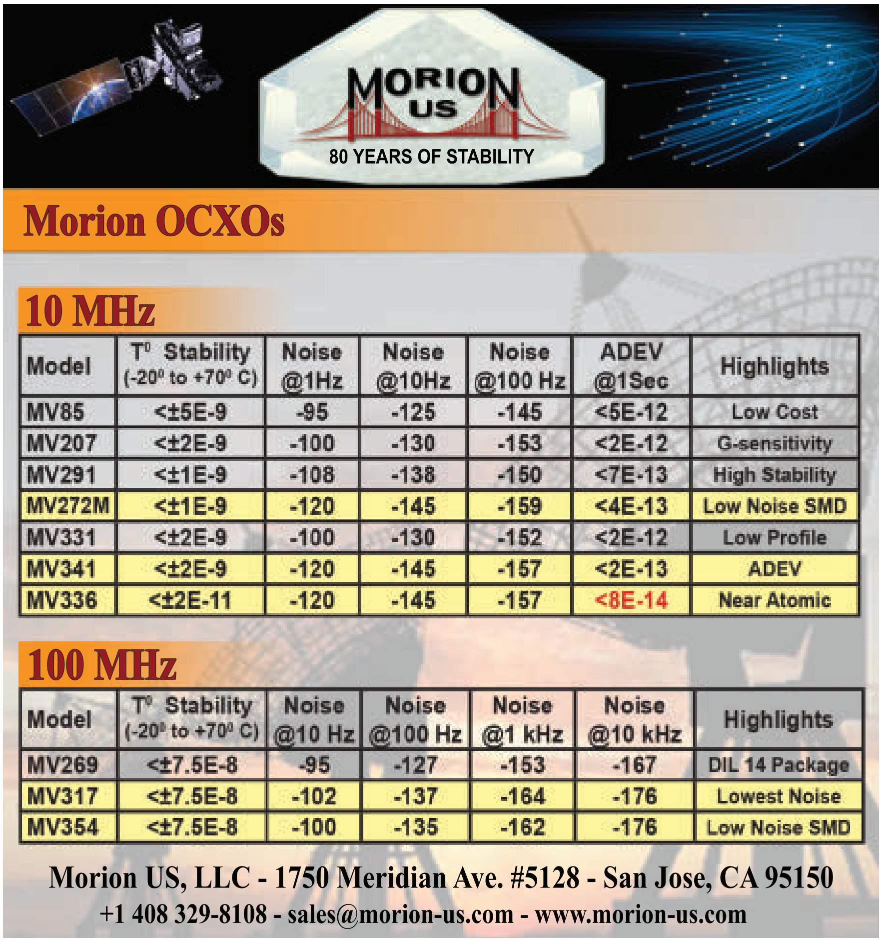
COMMON CELLULAR BANDS

Band	Uplink (MHz)	Downlink (MHz)	Duplex Type
1	1920 to 1980	2110 to 2170	FDD
3	1710 to 1785	1805 to 1880	FDD
4	1710 to 1755	2110 to 2155	FDD
7	2500 to 2570	2620 to 2690	FDD
17	704 to 716	734 to 746	FDD
25	1850 to 1915	1930 to 1995	FDD
40	2300 to 2400	2300 to 2400	TDD
41	2496 to 2690	2496 to 2690	TDD
66	1710 to 1780	2110 to 2200	FDD

achieving the necessary isolation between different bands, between the transmit and receive frequencies of each frequency division duplex (FDD) LTE band and between LTE and other wireless services, such as Wi-Fi and public safety communications. High performance acoustic filters are needed to achieve the required isolation. Bulk acoustic wave (BAW) filters provide better performance (higher Q factors) than surface acoustic wave (SAW) filters, especially at higher frequencies, and are typically used for the most demanding applications.

The isolation challenges increase with CA, because the RF front-end must communicate simultaneously on multiple bands. This leads to new requirements for cross-isolation between bands, to avoid situations where the transmit signal of one aggregated band interferes with receive signals on another aggregated band, which will degrade the sensitivity of the receiver. There are various problem scenarios. When aggregating widely separated frequency bands, issues can arise with harmonic frequencies generated at multiples of the transmit frequency by non-linear components in the RF chain, including power amplifiers (PA), switches and even filters. With some band combinations, such as bands 17 and 4 (see ***Table 1***), the third harmonic of the lower frequency band (17) falls into the receive frequency range of the higher frequency band (4), as shown in ***Figure 2***. To prevent interference, the filters in the RF front-end must provide very high rejection of the problem harmonics without adding unacceptable insertion loss. High linearity is required in all the components—PAs, switches, filters—to minimize the generation of harmonics.

A different cross-isolation issue occurs when aggregating closely spaced bands, which typically share the same RF pathway within the RF front-end. Examples include bands 1 and 3 and bands 25 and 66. In these cases, the problem is that the transmit frequency of one band is close to the receive frequency of the other aggregated band. Multiplexers, which combine all the transmit and receive filters for multiple aggregated bands into a single device, provide an efficient solution, allowing simultaneous use of the aggregated bands while providing isolation between them. Multiplexers will become increasingly important as network operators aggregate three or more



BNC Berkeley Nucleonics Corp

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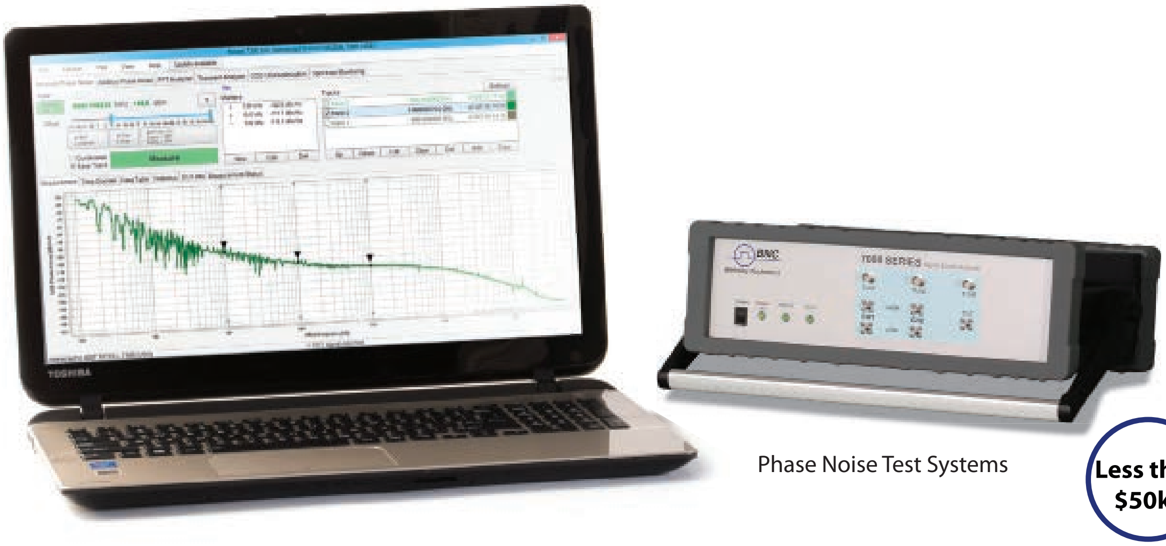

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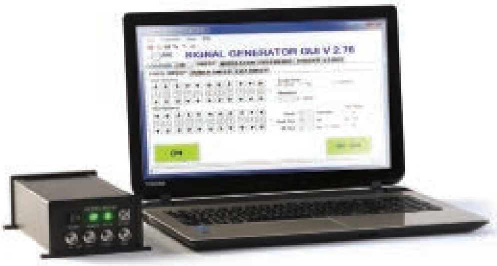
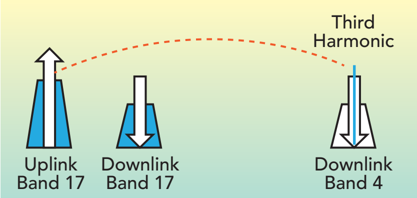


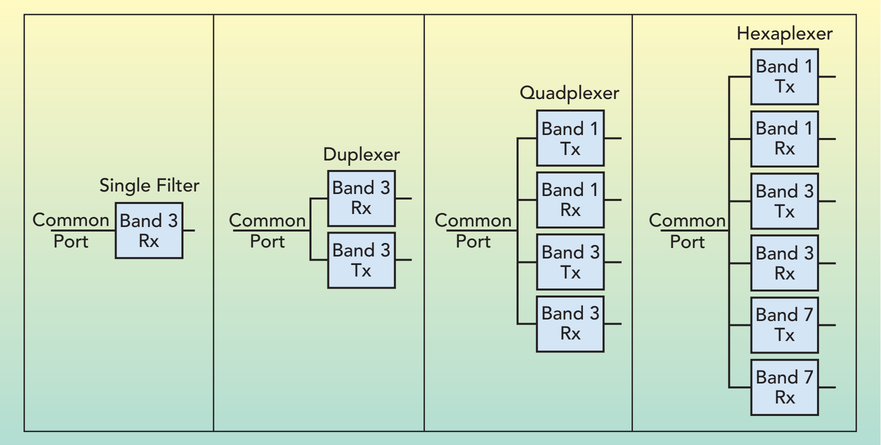
RF / Microwave Signal Sources

Real-Time Spectrum Analyzers



▲ **Fig. 2** **With carrier aggregation, the third harmonic of the Band 17 uplink signal can interfere with the receive signal in Band 4.**

bands (see ***Figure 3***), due to limits on the available space and number of antennas within the smartphone.



▲ **Fig. 3** **Multiplexers become increasingly important as network operators aggregate bands to increase data rates.**

Power Management

Several trends require better power management to maximize smartphone battery life and avoid overheating. Greater transmission bandwidth, achieved with techniques such as uplink CA, will require more power. Also, intra-band uplink CA, which combines component carriers within a single band, involves higher peak-to-average power ratios than standard LTE signals, increasing the demand on PA linearity. For example, doubling the uplink bandwidth with CA to 20 + 20 MHz (200 resource blocks) more than doubles the probability that the peak-to-average power ratio of the modulated signal envelope will exceed 4.5 dB.

Another emerging requirement is Power Class 2, a new standard that doubles output power to 26 dBm to overcome the greater propagation losses of high frequency bands (e.g., Band 41). The greater output power enables operators to maintain cell coverage as higher frequency bands are used, to add spectrum and support higher data rates. Thermal performance becomes critical at this higher power; reliability depends on maintaining acceptable device operating temperatures by efficiently dissipating the additional heat.

Envelope tracking (ET), which continuously adjusts the PA supply voltage to track the RF envelope and maximize PA efficiency, is spreading from flagship phones to mainstream use because it can reduce power consumption and heat dissipation. The increased efficiency provided by ET facilitates the use of broadband PAs, which minimizes the number of PAs required in handsets. However, the use of ET is limited to 20 to 40 MHz channels and will need to evolve to handle the wider bandwidth for applications such as intra-band uplink CA. (Editor's note: for further discussion of ET, read the article "Envelope Tracking in Handsets Solves a Network Problem" in this issue, page 102.)

Antennas

The number of antennas in smartphones has grown with the requirement to support faster data services as well as the growing range of RF frequencies and technologies. Today's handsets may include as many as six or seven antennas, including primary cellular and diversity receive (DRx), Wi-Fi, near field communications (NFC)

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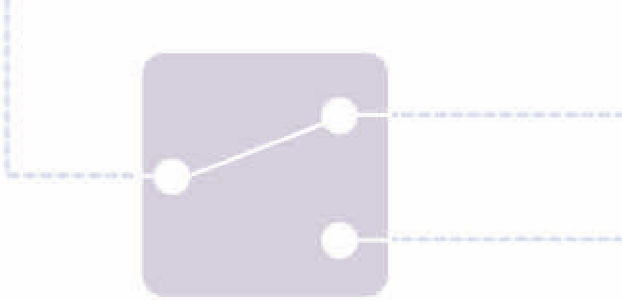

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CG2163X3	SPDT	6.0	0.40	0.50	40	31	+33 @ P1.0dB	+32 @ P1.0dB		(1.5 x 1.5 x 0.37)
JUST ADDED **CG2164X3**	DPDT	6.0	0.50	0.65	25	17	+32 @ P0.5dB	+30 @ P0.5dB		(1.5 x 1.5 x 0.37)
CG2176X3	Absorptive SPDT	6.0	0.45	0.55	30	22	+37.5 @ P0.5dB	+37.5 @ P0.5dB		(1.5 x 1.5 x 0.37)
CG2179M2	SPDT	3.0	0.45	N/A	26	N/A	+30 @ P0.1dB	NA		(2.0 x 1.25 x 0.9)
CG2185X2	SPDT	6.0	0.35	0.40	28	26	+29 @ P0.1dB	+29 @ P0.1dB		(1.0 x 1.0 x 0.37)
CG2214M6	SPDT	3.0	0.35	N/A	25	N/A	+30 @ P0.1dB	NA		(1.5 x 1.1 x 0.55)
JUST ADDED **CG2409M2**	SPDT	3.8	0.45	N/A	27	N/A	+37.5 @ P0.1dB	NA		(2.0 x 1.25 x 0.9)
JUST ADDED **CG2409X3**	SPDT	6.0	0.40	N/A	26	N/A	+37.5 @ P0.1dB			(1.5 x 1.5 x 0.37)
CG2415M6	SPDT	6.0	0.35	0.45	32	26	+31 @ P0.1dB	+31 @ P0.1dB		(1.5 x 1.1 x 0.55)
CG2430X1	SP3T	6.0	0.50	0.60	28	25	+28 @ P0.1dB	+28 @ P0.1dB		(1.5 x 1.5 x 0.37)

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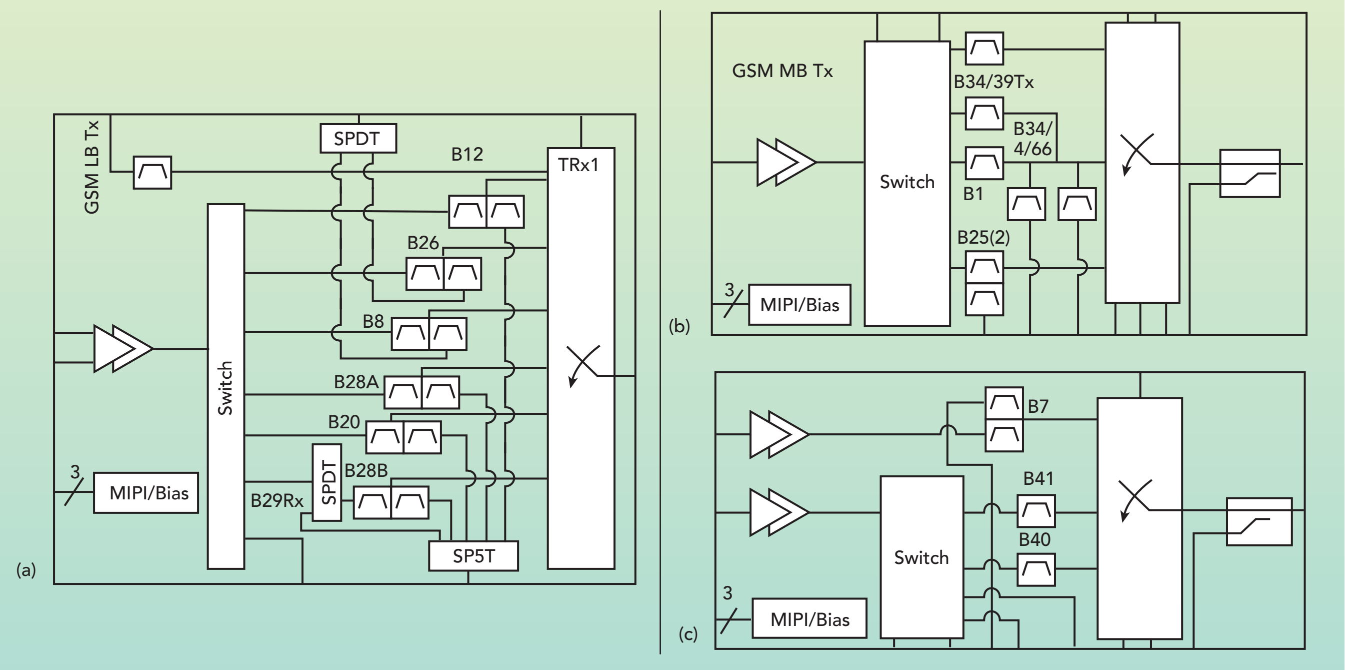

▲ Fig. 4 To handle all major cellular frequencies, smartphones integrate the PAs, switches and filters into three front-end modules that cover the low (a) mid (b) and high (c) bands.

and other standards. It becomes an increasingly difficult engineering challenge to fit more antennas into the limited physical space available within a typical handset. MIMO adds to the challenge, because it requires simultaneous transmission on multiple antennas. The need for additional antennas has been minimized by sharing the same antenna among multiple services that use similar frequencies, such as Bluetooth and Wi-Fi. Antenna sharing is also used to support faster Wi-Fi performance, enabling 2x2 MIMO Wi-Fi by sharing the LTE DRx antenna between LTE and a second Wi-Fi RF chain.

Antenna tuning, which adjusts antenna impedance to optimize efficiency at specific frequencies, has become increasingly prominent as a method to support the growing range of LTE frequencies.

RF Integration

Even though smartphones have become larger, mostly due to users' desire for larger screens, the space allocated to the RF front-end has not increased. In today's flagship phones, typically only 10 to 15 percent of the internal area is dedicated to cellular, Wi-Fi and Bluetooth RF functionality. Smartphones are getting thinner, reducing the internal volume, and manufacturers need to use the available space for new functionality and to maximize battery size to respond to user demands for longer operating time. As a result, the RF front-end must accommodate the growing complexity, including sup-


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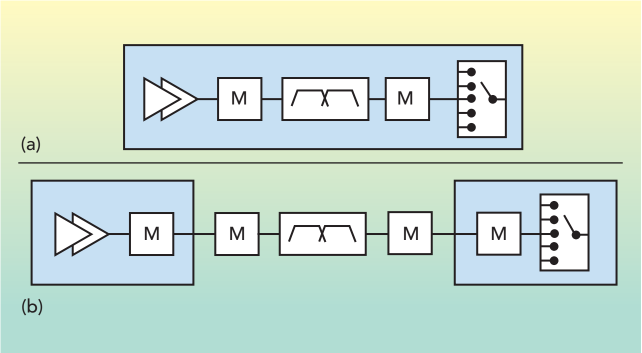
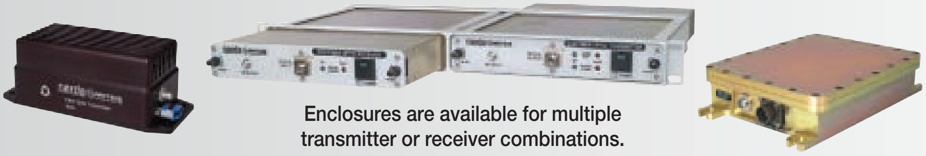


Fig. 5 Integrated front-end modules (a) can reduce losses by up to 0.5 dB compared to on-board matching (b).

port for a growing number of frequency bands, within roughly the same space. Higher levels of RF front-end integration are key to accommodating this growing RF complexity, particularly in flagship phones that support a large number of bands and CA combinations. Besides saving space, the integrated RF front-end modules simplify smartphone design, because many RF challenges are solved within the module rather than requiring the smartphone manufacturer to engineer solutions. This frees smartphone manufacturers to focus on other aspects of smartphone design, to attract consumers in an increasingly competitive market. By simplifying design, highly integrated modules also help smartphone makers accelerate time to market. Also, smartphone manufacturing yields are improved because there are fewer components that can fail.

An example of a highly integrated RF front-end architecture is Qorvo's RF Fusion, which includes support for all major LTE frequency bands in three compact placements: low, mid and high band (see ***Figure 4***). Each module includes PAs, switches and filters and uses advanced packaging to achieve space savings of 30 to 35 percent compared to the printed circuit board (PCB) area required for discrete components. Besides conserving valuable PCB real estate, this approach has several advantages: it improves performance by integrating components along each pathway, which eliminates the need for on-board matching, reduces losses by as much as 0.5 dB, reduces current consumption and the thermal load (see ***Figure 5***). Reducing losses makes it easier to meet handset manufacturers' performance targets. This integrated architecture also helps manage RF isolation, such as the interaction between bands aggregated for CA. For example, multiplexers supporting specific band combinations can be incorporated into each module. In the future, it may be possible to integrate an entire RF front-end into a single module, depending on whether the benefits to the manufacturer outweigh the additional cost of including bands that may not be used by the phone's owner.


LINK GAIN
GAIN (dB)
0
3
6
9
12
1
2
3
4
5
6
7
FREQUENCY
narda MITEQ
L3



SMARTPHONE TIERS

As smartphones continue to proliferate worldwide, the market has stratified into distinct tiers: flagship phones, which typically offer the highest performance and global band support, and mid-tier phones that deliver good performance and are designed primarily for domestic use, with only regional band support. Mid-tier phones have been popular in emerging markets such as Asia and Latin America, where consumers are price-sensitive. According to Strategy Analytics, smartphone tiers are here to stay; the company forecasts that mid-tier phones will account for 37 percent of handset volume by 2022, up from 32 percent in 2016. However, premium phones will continue to generate the bulk of global smartphone revenue because they sell for a much higher price.

This market stratification is reflected in RF front-end trends. Highly integrated RF front-end modules are typically seen only in premium handsets; mid-tier phones generally use a more discrete approach, such as Qorvo's RF Flex, giving handset manufacturers the flexibility to reduce component costs by including only the filters required for local frequency bands. As the RF environment becomes more complex, greater RF front-end integration will be seen in mid-tier phones. Market stratification has also spawned other trends, such as mid-tier phones that support dual SIMs. These enable users to minimize monthly costs, by using different services for voice and data or using local operators when traveling to different countries. Dual SIMs are supported with dual transceivers or techniques that use a single transceiver, such as time multiplexing.

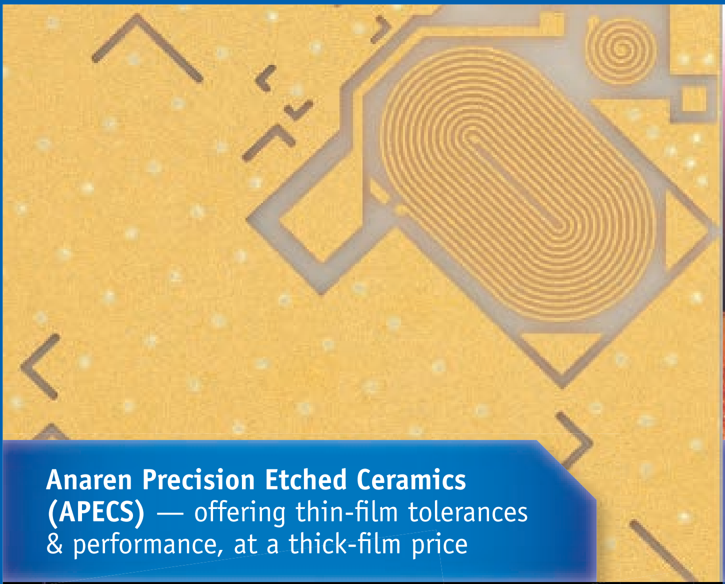
THE FUTURE RF FRONT-END

The smartphone RF front-end will continue to evolve and grow in complexity over the next few years to meet changing requirements. In addition to supporting 5G, the smartphone will likely assume the role of a hub for communications among rapidly proliferating IoT devices and sensors, which will require the integration of new air interfaces into the RF front-end.

5G specifications development currently focuses on three high-level use cases, including IoT:

- Enhanced mobile broadband, to support consumers' use of video and other data-intensive mobile applications, which will require lower latency as well as faster data rates
- Massive machine type communications for IoT applications; and
- Ultra-reliable and low latency communication for applications where reliability and performance are critical, such as autonomous vehicles.

5G specifications are due in two main phases: Phase 1 (3GPP Release 15), due in late 2018, will support a subset of use cases, including enhanced mobile broadband, and will focus on frequencies below 6 GHz. Currently, bands between 3.8 and 4.99 GHz are

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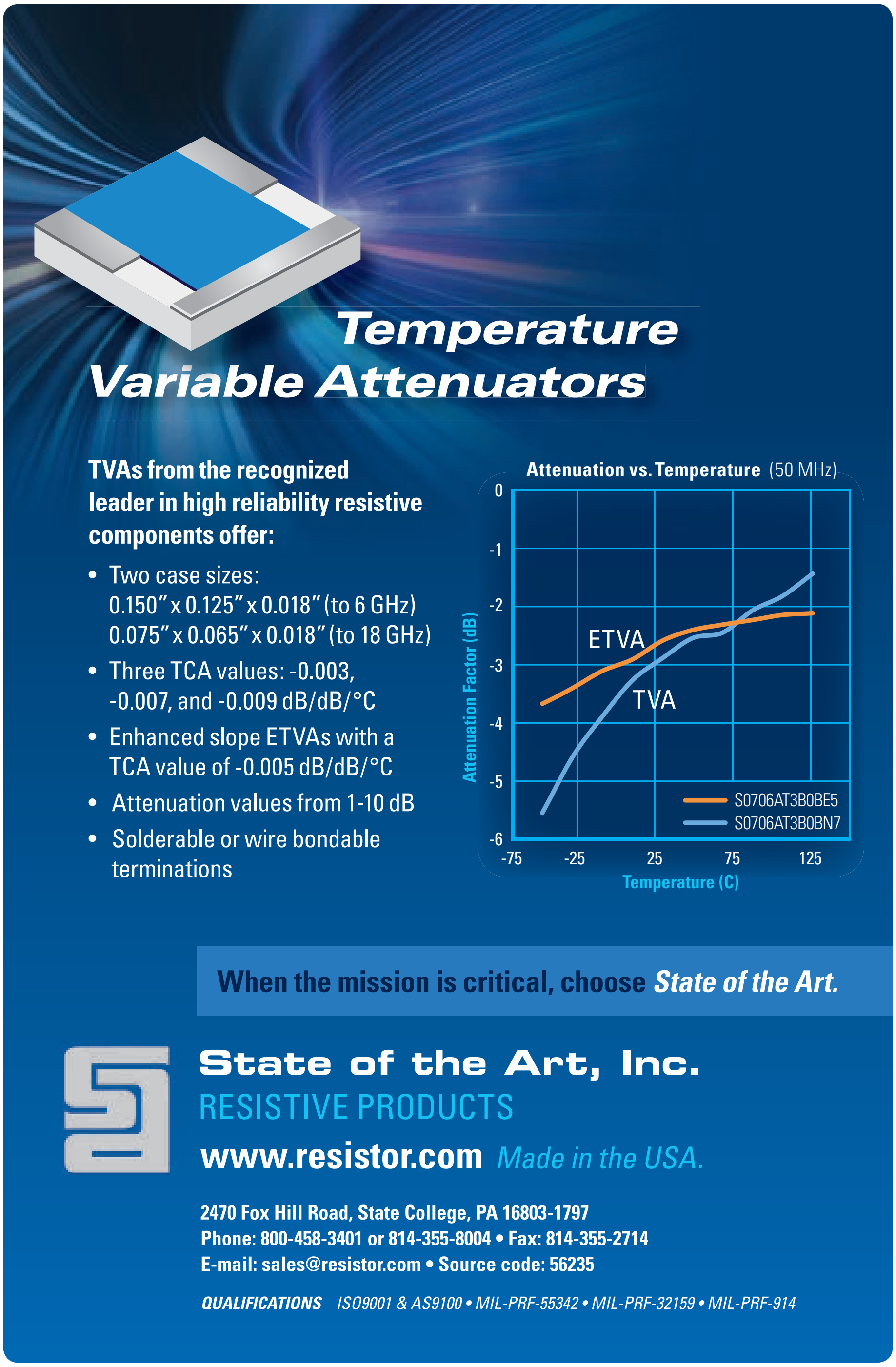
under consideration. Since 4G LTE will continue to be widely used, an important goal is to maximize coexistence by designing the specifications for the 5G new radio (NR) to minimize interference with 4G bands. In general, the RF front-end technologies required for 5G Phase 1 may be similar to those used for 4G LTE, with improvements to support the new requirements.

The main challenges for Phase 1 include PA performance and increased linearity to support new uplink requirements designed to improve performance for data-intensive applications. These encompass more complex modulation (e.g., 256-QAM) and optional cyclic prefix orthogonal frequency division multiplexing (CP-OFDM). The adoption of 4x4 MIMO to further boost data throughput will require increased integration and more complex switching, as well as increasing the number of antennas. Enhancements to bulk acoustic wave (BAW) filter technology, which is widely used for higher-frequency LTE bands, are being developed to meet the filtering requirements for the sub-6 GHz frequencies for 5G.



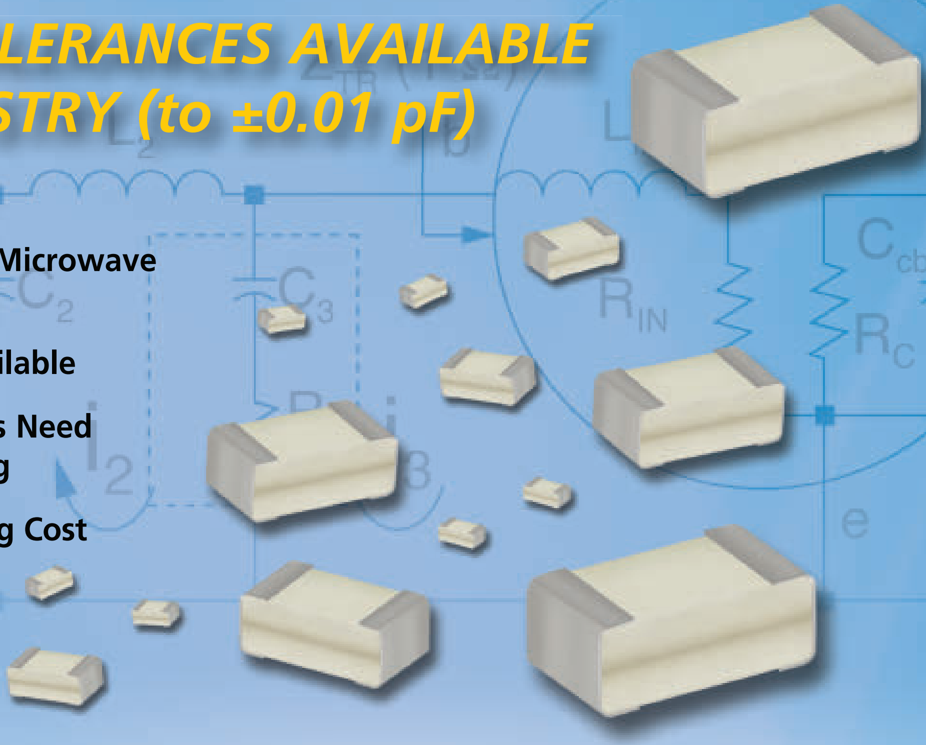
5G Phase 2 (3GPP Release 16), expected by the end of 2019, will include the remaining use cases and focus on much higher frequencies (28 GHz and above). Though specifications are at an earlier stage than Phase 1, it is clear that communications at millimeter wave frequencies will require radical new antenna array architectures, beamforming techniques and sophisticated algorithms to compensate for the greater path losses at these frequencies. Coexistence between the millimeter wave frequencies and 4G LTE will pose other challenges.

Tunable analog filters are being explored to reduce the number of filters in the RF front-end. However, it is extremely challenging to create a broadband tunable analog filter that meets the power handling, insertion loss, isolation and coexistence needs of modern smartphones. The adoption of CA, which requires simultaneous operation on multiple bands, introduces complications that make broadband tunable filters even more difficult to achieve.

Silicon technologies such as CMOS, SOI and SiGe will continue to spread throughout the RF front-end for control, switching and amplification. Nonetheless, GaAs offers performance advantages for PAs and is likely to remain the dominant PA process technology. Digital signal processing is increasingly being employed to improve front-end performance through functions such as digital predistortion (DPD) and ET.

CONCLUSION

The growing complexity of the RF front-end and the ever-improving performance will require a mix of many different technologies combined in highly integrated modules. Suppliers with the ability to design using such a wide range of technologies, including advanced filtering and millimeter wave, will be best positioned to succeed as the smartphone enters its second decade.■



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OCTAVE BAND LOW NOISE AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2110	0.5-1.0	28	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA12-2110	1.0-2.0	30	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA24-2111	2.0-4.0	29	1.1 MAX, 0.95 TYP	+10 MIN	+20 dBm	2.0:1
CA48-2111	4.0-8.0	29	1.3 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA812-3111	8.0-12.0	27	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA1218-4111	12.0-18.0	25	1.9 MAX, 1.7 TYP	+10 MIN	+20 dBm	2.0:1
CA1826-2110	18.0-26.5	32	3.0 MAX, 2.5 TYP	+10 MIN	+20 dBm	2.0:1

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

CA01-2111	0.4 - 0.5	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA01-2113	0.8 - 1.0	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3117	1.2 - 1.6	25	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3111	2.2 - 2.4	30	0.6 MAX, 0.45 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3116	2.7 - 2.9	29	0.7 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA34-2110	3.7 - 4.2	28	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA56-3110	5.4 - 5.9	40	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA78-4110	7.25 - 7.75	32	1.2 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA910-3110	9.0 - 10.6	25	1.4 MAX, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA1315-3110	13.75 - 15.4	25	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3114	1.35 - 1.85	30	4.0 MAX, 3.0 TYP	+33 MIN	+41 dBm	2.0:1
CA34-6116	3.1 - 3.5	40	4.5 MAX, 3.5 TYP	+35 MIN	+43 dBm	2.0:1
CA56-5114	5.9 - 6.4	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6115	8.0 - 12.0	30	4.5 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6116	8.0 - 12.0	30	5.0 MAX, 4.0 TYP	+33 MIN	+41 dBm	2.0:1
CA1213-7110	12.2 - 13.25	28	6.0 MAX, 5.5 TYP	+33 MIN	+42 dBm	2.0:1
CA1415-7110	14.0 - 15.0	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA1722-4110	17.0 - 22.0	25	3.5 MAX, 2.8 TYP	+21 MIN	+31 dBm	2.0:1

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA0102-3111	0.1-2.0	28	1.6 Max, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA0106-3111	0.1-6.0	28	1.9 Max, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-3110	0.1-8.0	26	2.2 Max, 1.8 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-4112	0.1-8.0	32	3.0 MAX, 1.8 TYP	+22 MIN	+32 dBm	2.0:1
CA02-3112	0.5-2.0	36	4.5 MAX, 2.5 TYP	+30 MIN	+40 dBm	2.0:1
CA26-3110	2.0-6.0	26	2.0 MAX, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA26-4114	2.0-6.0	22	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA618-4112	6.0-18.0	25	5.0 MAX, 3.5 TYP	+23 MIN	+33 dBm	2.0:1
CA618-6114	6.0-18.0	35	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA218-4116	2.0-18.0	30	3.5 MAX, 2.8 TYP	+10 MIN	+20 dBm	2.0:1
CA218-4110	2.0-18.0	30	5.0 MAX, 3.5 TYP	+20 MIN	+30 dBm	2.0:1
CA218-4112	2.0-18.0	29	5.0 MAX, 3.5 TYP	+24 MIN	+34 dBm	2.0:1

LIMITING AMPLIFIERS

Model No.	Freq (GHz)	Input Dynamic Range	Output Power Range Psat	Power Flatness dB	VSWR
CLA24-4001	2.0 - 4.0	-28 to +10 dBm	+7 to +11 dBm	+/- 1.5 MAX	2.0:1
CLA26-8001	2.0 - 6.0	-50 to +20 dBm	+14 to +18 dBm	+/- 1.5 MAX	2.0:1
CLA712-5001	7.0 - 12.4	-21 to +10 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1
CLA618-1201	6.0 - 18.0	-50 to +20 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	Gain Attenuation Range	VSWR
CA001-2511A	0.025-0.150	21	5.0 MAX, 3.5 TYP	+12 MIN	30 dB MIN	2.0:1
CA05-3110A	0.5-5.5	23	2.5 MAX, 1.5 TYP	+18 MIN	20 dB MIN	2.0:1
CA56-3110A	5.85-6.425	28	2.5 MAX, 1.5 TYP	+16 MIN	22 dB MIN	1.8:1
CA612-4110A	6.0-12.0	24	2.5 MAX, 1.5 TYP	+12 MIN	15 dB MIN	1.9:1
CA1315-4110A	13.75-15.4	25	2.2 MAX, 1.6 TYP	+16 MIN	20 dB MIN	1.8:1
CA1518-4110A	15.0-18.0	30	3.0 MAX, 2.0 TYP	+18 MIN	20 dB MIN	1.85:1

LOW FREQUENCY AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure dB	Power-out @ P1-dB	3rd Order ICP	VSWR
CA001-2110	0.01-0.10	18	4.0 MAX, 2.2 TYP	+10 MIN	+20 dBm	2.0:1
CA001-2211	0.04-0.15	24	3.5 MAX, 2.2 TYP	+13 MIN	+23 dBm	2.0:1
CA001-2215	0.04-0.15	23	4.0 MAX, 2.2 TYP	+23 MIN	+33 dBm	2.0:1
CA001-3113	0.01-1.0	28	4.0 MAX, 2.8 TYP	+17 MIN	+27 dBm	2.0:1
CA002-3114	0.01-2.0	27	4.0 MAX, 2.8 TYP	+20 MIN	+30 dBm	2.0:1
CA003-3116	0.01-3.0	18	4.0 MAX, 2.8 TYP	+25 MIN	+35 dBm	2.0:1
CA004-3112	0.01-4.0	32	4.0 MAX, 2.8 TYP	+15 MIN	+25 dBm	2.0:1

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Underwater Radio, Anyone?

With his newly announced A Mechanically Based Antenna (AMEBA) effort, program manager Troy Olsson of DARPA's Microsystems Technology office is betting on a little exploited aspect of electromagnetic physics that could expand wireless communication and data transfer into undersea, underground and other settings where such capabilities essentially have been absent. The basis for these potential new abilities are ultra-low frequency (ULF) electromagnetic waves, ones between hundreds of Hz and 3 KHz, which can penetrate some distance into media like water, soil, rock, metal and building materials. A nearby band of very low frequency (VLF) signals (3 to 30 KHz) opens additional communications possibilities because for these wavelengths the atmospheric corridor between the Earth's surface and the ionosphere—the highest and electric-charge-rich portion of the upper atmosphere—behaves like a radio waveguide in which the signals can propagate halfway around the planet.

"If we are successful, scuba divers would be able to use a ULF channel for low bit-rate communications, like text messages, to communicate with each other or with nearby submarines, ships, relay buoys, UAVs and ground-based assets. Through-ground communication with people in deep bunkers, mines or caves could also become possible," Olsson said. And because of that atmospheric waveguide effect, VLF systems might ultimately enable direct soldier-to-soldier text and voice communication across continents and oceans.

To date, there's been a huge and expensive rub to actually pulling off low-frequency radio communication in the versatile ways that Olsson has in mind. The wavelengths of VLF and ULF radio signals rival the distances across cities and states, respectively. And since longer wavelengths have required taller antennas, communications in these frequency bands have entailed the construction of enormous and costly transmitter structures. A VLF antenna that the Navy built on a remote peninsula in Cutler, Maine, in the heat of the Cold War just to send a trickle of data to submarines makes the point: the gargantuan transmitter complex occupies 2,000 acres, features 26 towers up to 1,000 feet high and operates with megawatt levels of power.

With the AMEBA program, Olsson aims to develop entirely new types of VLF and ULF transmitters that are sufficiently small, light, and power efficient to be carried by individual warfighters, whether they are on land, in the water or underground. Rather than relying on electronic circuits and power amplifiers to create oscillating electric currents that, when driven into antennas, initiate radio signals, the new low-frequency VLF and ULF antennas sought in the AMEBA program would generate the signals by mechanically moving materials harboring strong electric or magnetic fields.

In principle, this is as simple as taking a bar magnet or an electret—an insulating substance, such as a cylinder of quartz (silica) glass, in which positive and negative electric charges are permanently segregated to create an electric dipole—and moving it at rates that will generate ULF and VLF frequencies. Challenges include packing more powerful magnetic and electric fields into smaller volumes with smaller power requirements than ever achieved before, that will require innovations in chemistry and materials, design and mechanical engineering.

DARPA Image

SM-6 Intercepts Ballistic Missile Target at Sea

VIEW VIDEO

The U.S. Navy fired two Standard Missile-6 Dual I guided missiles, developed by Raytheon Missile Systems, from the USS JOHN PAUL JONES (DDG-53) during a recent test event, intercepting a medium-range ballistic missile target at sea in its final seconds of flight. The SM-6 is the new Sea-Based Terminal variant of the company's versatile missile portfolio.

The SM-6 Dual I achieved initial operating capability in 2016, and is on track to achieve final operating capability. It was first tested in a successful flight test mission in August 2015.

The U.S. Missile Defense Agency's Sea-Based Terminal program will protect against ballistic threats in their terminal phase of flight by using SM-6 missiles integrated into the Aegis integrated missile guidance system.

SM-6 provides U.S. Navy vessels with extended-range protection against fixed- and rotary-wing aircraft, unmanned aerial vehicles, cruise missiles and ballistic missiles in the terminal phase of flight, and an offensive capability against surface targets.

In April 2015, Raytheon delivered the first full-rate production SM-6 from its $75 million, 70,000 square foot SM-6 and Standard Missile-3 all-up-round production facility at Redstone Arsenal in Huntsville, Ala. Ray-

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theon has delivered more than 315 SM-6 missiles with continuing production.

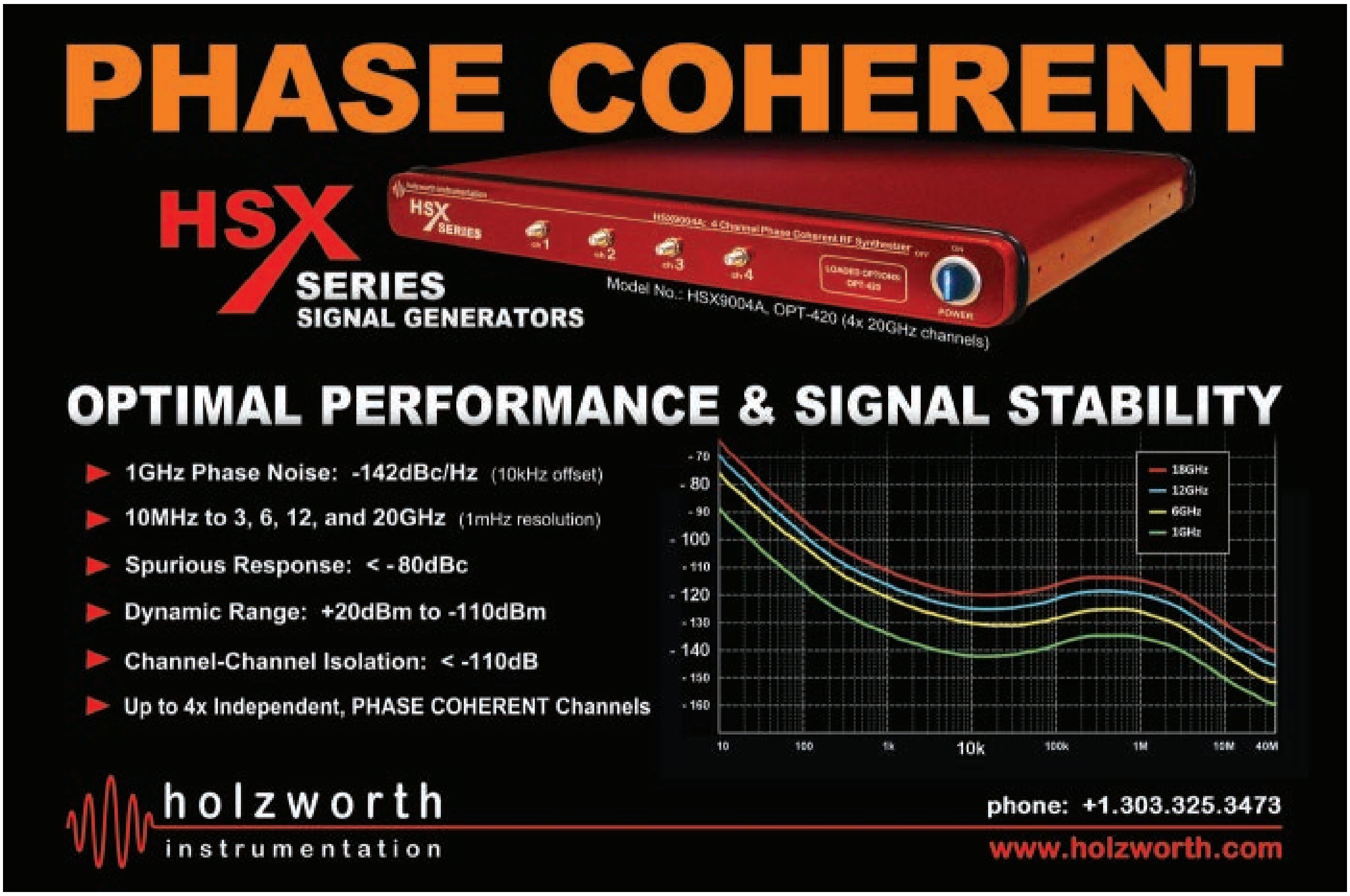
U.S. Navy Photo

Steady Growth Expected for Global EW Market Through 2026

The global electronic warfare market is expected to be $14.4 billion in 2016, and will grow at a CAGR of 3.13 percent, to a value of $19.6 billion by 2026. The cumulative global market for electronic warfare will reach $184.1 billion over the forecast period. Demand is anticipated to be driven by rapid technology advancements and the growing need for intelligence, surveillance, and reconnaissance (ISR) capabilities in militaries globally. Modern warfare places a greater emphasis on information superiority and situational awareness, and this is expected to be a major factor driving spending.

The market includes three segments; electronic protection, electronic attack and electronic warfare support. The largest share is projected to be for by electronic protection systems with an estimated 50 percent over the forecast period. This is followed by electronic warfare support systems with 32 percent and electronic attack systems with 18 percent.

The U.S., which has historically been the largest market, has several ongoing projects in this sphere. For example, the U.S. Navy has contracted Raytheon Co. for the development of a critical electronic attack program for the war fighters, under the Next Generation Jammer project. Additionally, DARPA is also working on the Adaptive Radar Countermeasures (ARC) program, which aims to develop electronic warfare capability to combat hostile adaptive radar systems. More recently, the U.S. has initiated a new electronic warfare planning and management tool that permits army personnel to synchronize and integrate a host of electronic warfare signals. This tool is expected to be fully developed and operational by 2022.



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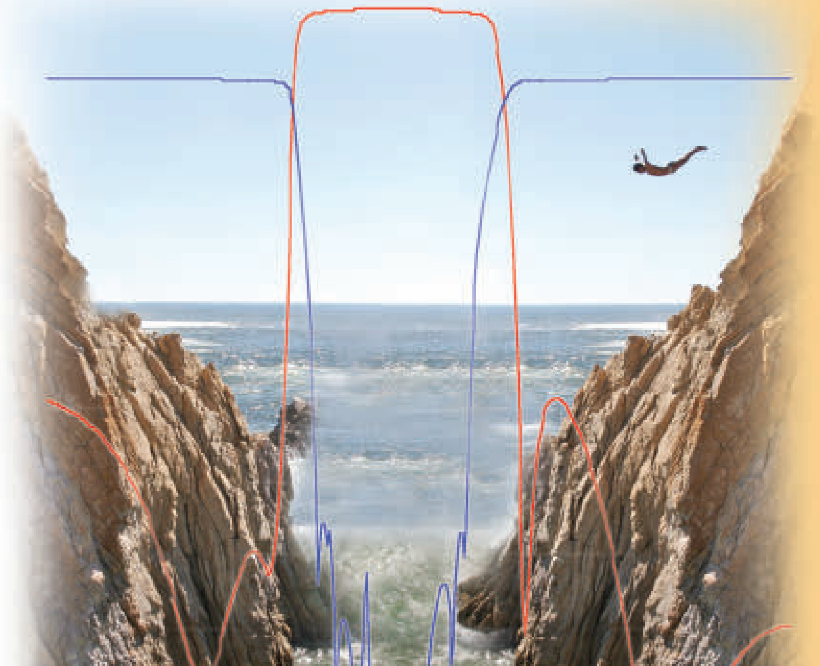

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Thales Equips French Forces with Spy'Ranger UAVs

Thales's latest-generation Spy'Ranger mini surveillance and reconnaissance Unmanned Aerial Vehicle (UAV) has been chosen by the French Defence Procurement Agency (DGA) to equip the French forces. Up to 70 mini-UAV reconnaissance systems (SMDR) will be made available from 2018. Each system consists of three mini-UAVs, a ground segment and the associated technical support.

The Spy'Ranger is the new 'eye in the sky' for the combined arms tactical group, able to be operated in a standalone mode or connected to a Command, Control, Computers, Communications and Intelligence (C4I) system. It is specifically tailored to the needs of the armed forces, as well as to those of essential operators. Spy'Ranger will provide a decisive tactical advantage by offering the capacity to observe day or night, for long periods of time and at a distance of up to 30 km.

Developed by Thales in cooperation with French SMEs Aviation Design and Merio in under 13 months, Spy'Ranger will offer French Forces a number of innovations that provide real capability gains and markedly contribute to the gathering of frontline intelligence and to the protection of forces in operation.

Fully adapted to frontline air-land intelligence missions in battlefields in hostile environments (climate, electromagnetic, physical, etc.), the Spy'Ranger has been designed to optimise life cycle costs. Its gyro-stabilized multi-sensor optronic payload is claimed to have the highest resolution in the world for this range of platform, facilitating the positive identification of zones or objects over which it has flown. Its tactical data link, protected to the highest standard, offers high speeds enabling the transmission of high-definition image streams and its command and control software (C2) provides an effective user interface.

Source: Thales

CW and Partners Drive Forward IoT Innovation

Cambridge Wireless (CW) has been selected by the Digital Catapult to deliver IoTUK Boost, a Government-funded programme of support to help UK SMEs and entrepreneurs develop Internet of Things (IoT) enabled services and applications in Cambridge—using low power wide area networks (LPWAN).

As one of six partners selected across the UK, the CW programme will make use of the city-wide LoRaWAN network, which is currently being deployed by the Smart Cambridge programme as part of its work with the Greater Cambridge City Deal. The company has formed a core partnership with Everynet, the LoRa Alliance™, Iotic Labs and Smart Cambridge, which will be supported by the University of Cambridge and a variety of technology businesses as the programme gathers pace.

At least 10 companies will be selected to participate in the programme. Successful SMEs will be coached in the development of market-ready products and services and provided with training and development kits. Winning solutions will be showcased at the CW International Conference in the summer of 2017.

Robert Driver, CEO of CW, said, "CW is delighted to be part of this partnership. We are one of only six successful organizations across the country delivering this important national programme. A key role of CW is to bring together companies—both large and small—to share knowledge and insights. We are also thrilled to be joining up with Smart Cambridge so that the developed solutions can have a direct impact on the city. "

Tracy Hopkins, GM Everynet and Marketing Committee Chair of the LoRa Alliance said, "The LoRaWAN ecosystem is the largest in the LPWA industry and this will encourage innovation and creativity to solve real world city wide issues. We have moved beyond technology in the LPWA space and it is all about solutions that deliver commercially as well as technically. The LoRa Alliance is very pleased to endorse programmes of this type as innovation is key to maximizing the impact of the IoT."

Graphene Gets Mass Production Boost

While there is no denying the potential of graphene, its mass production has so far been hindered by laborious fabrication methods and the high costs they entail. A new technique developed by partners of the carbon resistive random ac-

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cess memory materials (CARERAMM) project promises to overcome these problems.

The new production method was developed by engineers at the University of Exeter, UK, which creates entire device arrays directly on the copper substrates used for the commercial production of graphene, after which complete and fully-functional devices can be transferred to a substrate of choice.

This process has been demonstrated by producing a flexible and completely transparent graphene oxide-based humidity sensor. One of the team's main objectives was to increase the range of surfaces that graphene devices can be put on. Whilst the demonstrated humidity sensor was integrated in a plastic film, other materials such as silicon and textiles can also be considered.

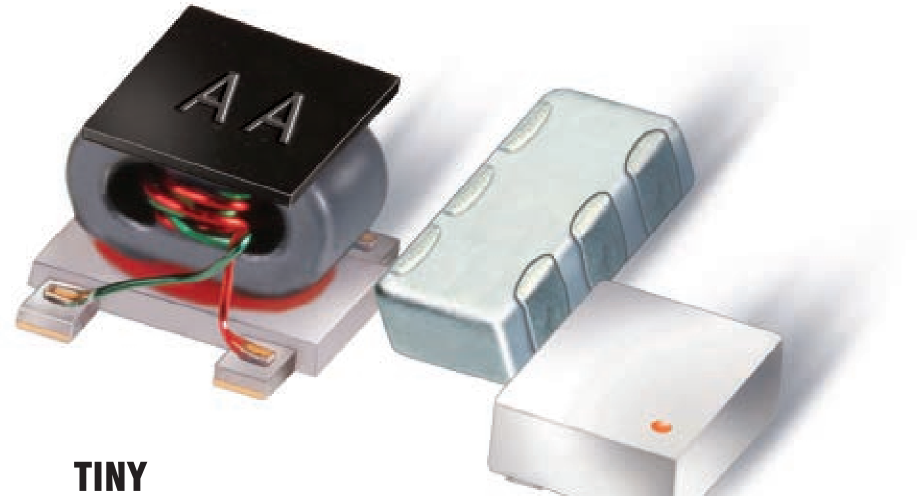
Professor Monica Craciun from Exeter University's engineering department commented, "The University of Exeter is one of the world's leading authorities on graphene, and this new research is just the latest step in our vision to help create a graphene-driven industrial revolution. High-quality, low cost graphene devices are an integral part of making this a reality, and our latest work is a truly significant advance that could unlock graphene's true potential."

ESF Launches Science Connect

The European Science Foundation (ESF) has launched Science Connect, its new, expert services division, which will be dedicated to providing practical and interdisciplinary support services to the science community and science stakeholders in Europe.

Building on ESF's extensive network and experience, Science Connect will deliver expert resources, tools and metrics to support the effective administration of science projects in both the private and public research sector. As the research landscape has evolved, so has ESF's role in supporting scientific endeavours. With this new division the organisation remains committed to providing valued and effective services to its Member Organisations and science stakeholders in Europe and beyond.

Jari Kinaret, director of the EU-funded Graphene Flagship, said, "ESF administered the competitive call of the Graphene Flagship, which is one of the largest collaborative research programmes launched by the European Commission, and we are impressed by the organization's professionalism in managing large international research calls."



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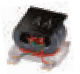

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Electrical Performance

Exposed Terminals for
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Tiny Size
3 x 3 x 1.14 mm high

Low NF from 0.5 dB *High IP3 up to +42 dBm* *Low DC current 65 mA* from $7.45 ea. *(qty 20)*

When failure is not an option! Our CMA family of ceramic MMIC amplifiers is expanding to meet your needs for more critical applications. Designed into a nitrogen-filled, hermetic LTCC package just 0.045" high, these rugged models have been qualified and are capable of meeting MIL standards for a whole battery of harsh environmental conditions:

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**Gross leak only*

Robust performance across wide bandwidths makes them ideal for military and defense applications, hi-rel instrumentation, and anywhere long-term reliability adds bottom-line value. Go to minicircuits.com for all the details today, and have them in your hands as soon as tomorrow!

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3 x 3 x 1.14 mm

Model	Freq. (GHz)	Gain (dB)	P_{OUT} (dBm)	IP3 (dBm)	NF (dB)	DC (V)	Price $ ea. (qty 20)
CMA-81+	DC-6	10	19.5	38	7.5	5	8.95
CMA-82+	DC-7	15	20	42	6.8	5	8.95
CMA-84+	DC-7	24	21	38	5.5	5	8.95
CMA-62+	0.01-6	15	19	33	5	5	7.45
CMA-63+	0.01-6	20	18	32	4	5	7.45
CMA-545+	0.05-6	15	20	37	1	3	7.45
CMA-5043+	0.05-4	18	20	33	0.8	5	7.45
CMA-545G1+	0.4-2.2	32	23	36	0.9	5	7.95
CMA-162LN+	0.7-1.6	23	19	30	0.5	4	7.45
CMA-252LN+	1.5-2.5	17	18	30	1	4	7.45

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4 Billion IoT Devices Will Rely on LPWAN Technologies by 2025

VIEW VIDEO

With four billion IoT devices expected to rely on Low Power Wide Area Networks (LPWAN) by 2025, this technology will be the fastest growing connectivity segment in the market through 2025. The rise of LPWANs will translate into one billion chipset shipments with the technology generating a total value of more than $2 billion in 2025.

"The success, or otherwise, of different LPWAN technologies at stake will much depend on the market they are targeting case by case," says Samuel McLaughlin, research analyst at ABI Research. "Regardless of the targeted use case, LPWAN technology suppliers should aim to create solid ecosystems around their technologies by either partnering with service platform providers or building one of their own. Otherwise, they will face serious hurdles in this fast-moving and highly competitive market."

> "...suppliers should aim to create solid ecosystems around their technologies..."

LPWAN can be split into two main categories; technologies that operate under unlicensed spectrum and those operating under licensed spectrum and using 3GPP standards. Although unlicensed technologies—whether proprietary technologies like SIGFOX or those based on open frameworks like LoRa and Weightless—are gaining a considerable momentum within the IoT market, they will be increasingly challenged by the emerging technologies based on 3GPP standards, notably NB-IoT.

"LPWAN technologies operating under unlicensed spectrum have the early market advantage and provide the quickest time to deployment, and the lowest infrastructure and operating costs for many IoT applications," continues McLaughlin. "However, emerging 3GPP LPWAN technologies like eMTC and NB-IoT are promising similar performance and have many more advantages. These include strong support from the telecommunications ecosystem, the ability to operate ubiquitously across the cellular infrastructure already in place, and most importantly, the scalability for service providers to easily and quickly add new services to their portfolios using the same infrastructure."

While some technologies, mainly those operating in unlicensed spectrum, will continue to perform well in specific segments, notably utility and energy management, as well as in retail applications, other technologies will better suit service providers who want to address many segments using the same infrastructure. Smart cities, smart homes, smart buildings and industrial IoT applications are prime examples of such segments. Operators including Orange and SK Telecom are deploying various technologies operating in both licensed and unlicensed spectrums with the ultimate goal being to build service platforms that are agnostic to the access technology used. Their aim is to play the various LPWAN technologies at their strengths, depending on the market segment targeted."

The utility and energy management market will hold the largest share of the LPWAN market through 2025 due to the fact that the application requirements of smart electricity, water and gas meters match fundamental characteristics of LPWAN technologies, such as long battery life, wide coverage area and higher link budget.

NB-IoT Availability Will Push Cellular M2M Module Shipments Past 400 Million

Several mobile operators, including DT, Vodafone, China Mobile and China Unicom announced NB-IoT network availability as early as 2017, according to Dan Shey, managing director and vice president at ABI Research. "While this may not equate to full regional coverage across all operator properties nor service availability, it demonstrates operator commitment to the technology to help drive OEM product development and eventual customer adoption," Shey said.

Tracking, as well as simple thing monitoring and control, will be the primary application segments for NB-IoT. With decreased technology requirements enabling long battery life and greater coverage, tracking of all types of products will be possible. In fact, in Turkey and Spain pre-standard NB-IoT is used to connect sensors in a car park, allowing drivers with a smartphone application to locate available parking spaces. In time, NB-IoT-based devices purchased straight from a local supermarket should be available to consumers for sharing economy applications.

Operator NB-IoT announcements are also a response to continued pressure by the proprietary LPWA technology suppliers, whose low-cost network and module costs also create a compelling business case for tracking and asset monitoring markets. Some operators, such as KPN, Orange, SK Telecom and Softbank, already completed, or are currently rolling out, LoRa networks first before rolling out Cat M or NB-IoT networks.

Cat M network deployments will be slightly delayed mainly in Europe and parts of Asia Pacific due to NB-IoT network deployment acceleration. However by 2021, Cat M shipments will not be suppressed by NB-IoT over previous forecasts because of its throughput advantages over NB-IoT in app segments of metering and security, and because North American operators are pushing this technology ahead of NB-IoT.

For More Information
Visit mwjournal.com for more commercial market news.

New Threats Emerge as Broadcom and Qualcomm Dominate GNSS IC Vendors

The GNSS market landscape is expanding due to the rapid growth of GNSS-enabled wearables and unmanned aerial vehicles (UAV) coupled with new innovation opportunities around low-cost precision GNSS. In its latest GNSS IC vendor competitive analysis, ABI Research determined Broadcom and Qualcomm remain the two top IC vendors for the fourth year in a row with a mere two points separating MediaTek in third from u-blox in fourth. New threats emerge to shake up the landscape in the years ahead, though, with CEC Huada and Samsung now companies to watch.

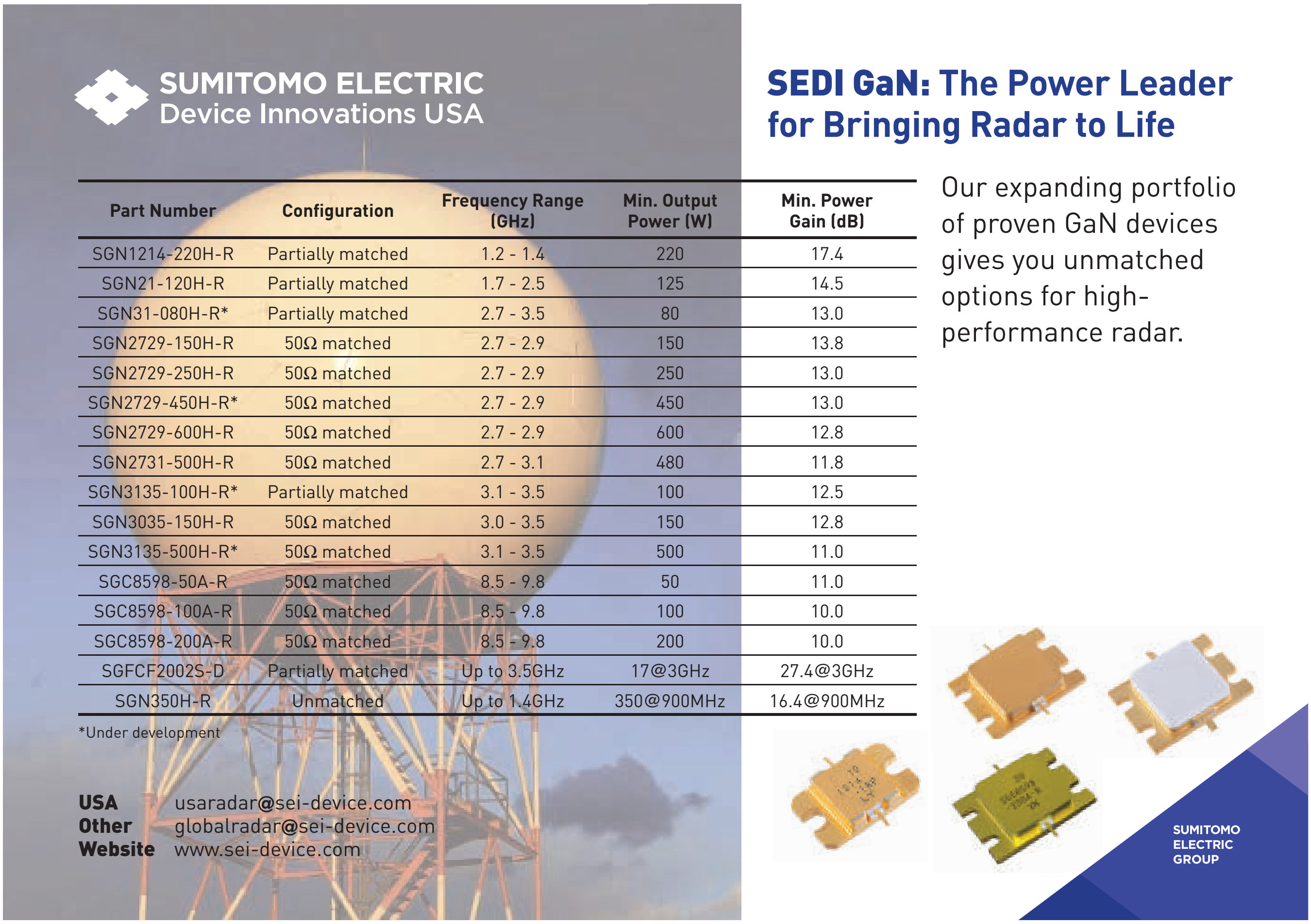
"MediaTek and u-blox once again swapped places," says Patrick Connolly, principal analyst at ABI Research. "U-blox had another stellar year financially and, along with Skytraq, led the way on low-cost precision GNSS with its NEO-M8P module. MediaTek, which showed significant success in wearables and smartphones, transitioned back to third place primarily due to growing market share."

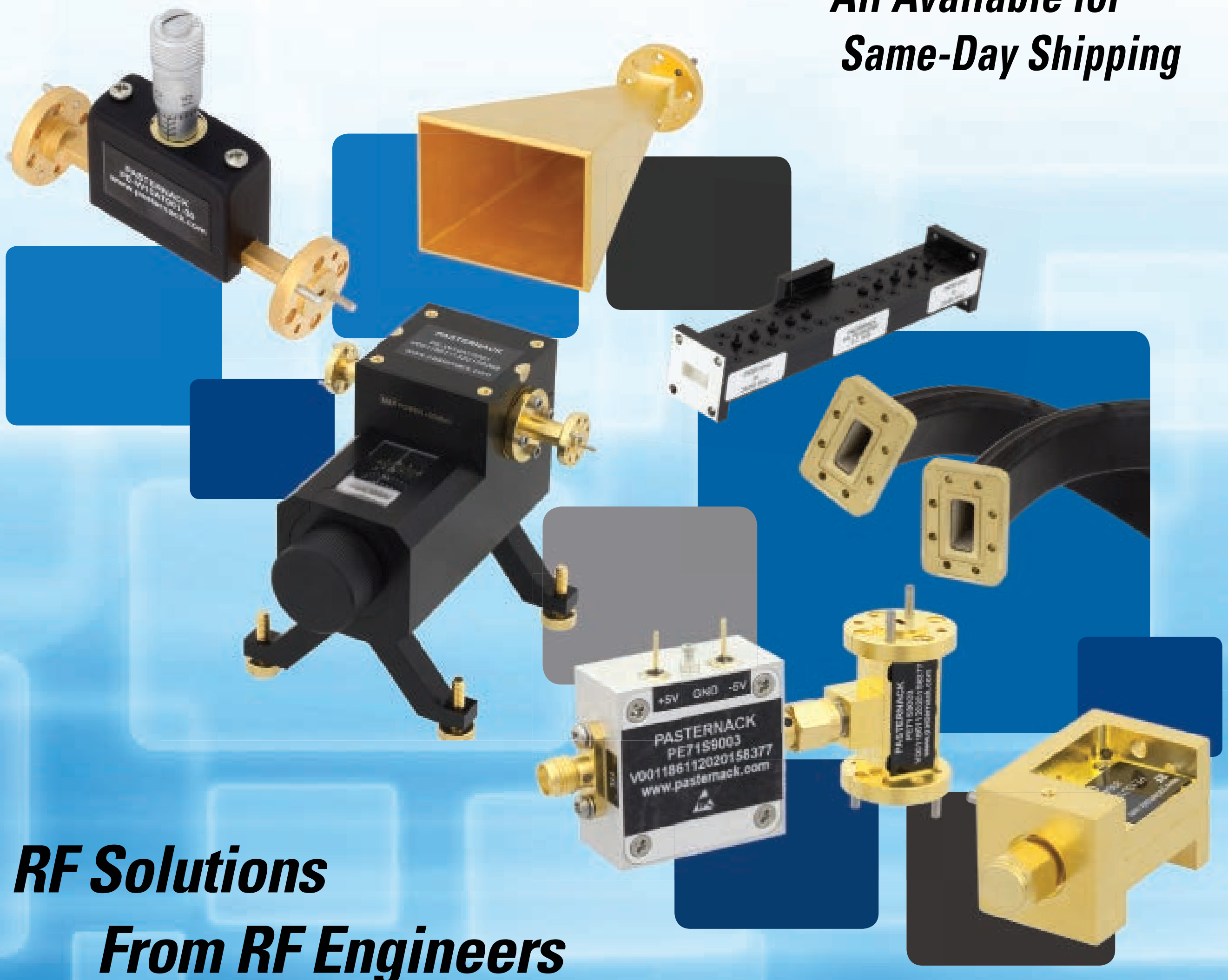
Broadcom and Qualcomm remain the two top GNSS IC vendors. Within the past year, Broadcom spurred more headlines with its wearables success and its initial work on L1/L5 dual-frequency receivers. Qualcomm continues to lead in total GNSS shipments, as well as innovative new technologies like LED/VLC and LTE Direct. Its partnership with Baidu on its IZat™ platform is also notable and represents the beginning of the era of "always on, ubiquitous location technologies."

But the incumbents are not the only players to watch in this evolving market. CEC Huada and Samsung sit poised to instill great change in the market landscape, as their innovation over the past 12 months serves to prove.

> CEC Huada and Samsung are poised to instill change in the market landscape.

"CEC Huada developed single frequency RTK GPS, as well as BDS receivers and INS/MEMS receivers, which the company released to select customers in 2016," concludes Connolly. "And it is now developing a dual frequency BDS receiver and a receiver for IRNSS. Samsung, meanwhile, launched its first embedded GNSS solution, the Exynos CPU chipset. Given its presence across so many GPS-enabled consumer electronic devices, the company looks set to be a major disruptor in the coming years."

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Around the Circuit

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

MACOM sold the former Metelics Londonderry Point Contact Diode Product Line to **Massachusetts Bay Technologies**, located at 378 Page Street, Stoughton, Mass. This product line will be fully functional starting in January 2017. Please direct all new and/or current commercial or military point contact diode requirements to Charlie Fallon, vice president, Massachusetts Bay Technologies at (781) 344-8809 or sales@massbaytech.com.

Infinite Electronics has acquired **KP Performance Antennas**, an Edmonton, Canada based manufacturer of broadband antennas and accessories. Founded in 2008, KP formed a strong team of experienced professionals focused on the design, development and manufacture of solutions for the Wireless Internet Service Provider (WISP) market. Their concentration on exceptional customer service and technical support has created a loyal, growing customer base, many of which consider KP a strategic partner. Based in Irvine, Calif., Infinite Electronics offers a broad range of RF components, assemblies and wired/wireless connectivity solutions, serving the aerospace/defense, industrial, government, consumer electronics, instrumentation, medical and telecommunications markets.

Leonardo-Finmeccanica has acquired the full control of **Sistemi Dinamici S.p.A** from **IDS S.p.A** in December 2016. The control of the company, which involved the remaining 60 percent of shares, is aimed at further strengthening the commitment of Leonardo in unmanned products thanks to the acquisition of the new unmanned lightweight helicopter SD-150 Hero programme. Leonardo now widens its unmanned helicopter portfolio, which also includes the SW-4 Solo, and consolidates its capabilities as a system integrator, developing both platforms, equipment and sensors.

Admiralty Partners Inc., an investment firm focused exclusively on acquisitions in the global aerospace and defense sectors, announced that an affiliate has acquired **GE's** Santa Ana, Calif. operations. The Santa Ana business will continue to operate in its present Southern California location under the name **Integral Aerospace LLC**. Tracing its roots back over 50 years, today Integral Aerospace is a manufacturer of flight-critical products for military and commercial aircraft, including landing gear components, carbon fiber filament-wound external fuel tanks for U.S. Navy aircraft, aircraft mounted fuel pumps and a variety of complex machined structures and engine components.

COLLABORATIONS

Qualcomm Technologies, **Ericsson** and **AT&T** have announced plans to conduct interoperability testing and over-the-air field trials based on the expected 5G New Radio (NR) specifications being developed by 3GPP, which will form the basis of the global standards. The trials intend to help move the mobile ecosystem to faster 5G deployment based on standards-compliant 5G NR infrastructure and devices once 3GPP completes the first release of the official specifications, which is expected as part of Release 15. The trials will support operation in millimeter wave spectrum, aiming to accelerate commercial deployments in the 28 and 39 GHz Bands.

Huawei, a global ICT solutions provider, has chosen a test solution from **Rohde & Schwarz** based on the R&S SMW200A vector signal generator and the R&S FSW signal and spectrum analyzer to perform NB-IoT base station tests in line with Release 13 Cat-NB1. The Huawei eRAN 12.0 wireless version is tested using the Rohde & Schwarz solution in compliance with 3GPP TS 36.141. The air interface performance test includes 52 test cases covering power, EVM, spectrum emission, receiver sensitivity, coverage capability, and a multitude of other aspects. All test cases were passed with satisfactory results.

NEW STARTS

Precision finishing house **Centerline Technologies** has expanded its wafer dicing capabilities. With over a decade of experience in sizing, William Fagan stepped in as department manager to oversee growth as the company acquired six new diamond saws. The onboarding of Fagan and acquisition of new equipment allow greater capacity in order to meet a rising demand.

ACHIEVEMENTS

Anritsu Co. announced that its Signaling Tester MD8430A received the Best VoLTE or LTE Broadcast Product award at the 2016 5G & LTE North America Awards held November 14-16 in Dallas, Texas. The MD8430A was recognized for its innovation and exceptional impact for R&D test within the LTE eco-system. For the awards, 5G & LTE North America enlisted an expert panel of impartial industry analysts who judged each category based on given criteria. For the Best VoLTE or LTE Broadcast award, submissions were judged on the nature of the product or service, the impact and true contribution to VoLTE/LTE Broadcast applications, and the impact on future networks.

RLC Electronics Inc. announced the achievement of AS9100 Rev C Certification. AS9100 is the internationally recognized quality management system standard specific to the aerospace, aviation and defense industries. This standard is strongly supported and adhered to by major aerospace OEMs and is being required by vendors within the supply chain on an increasing basis. AS9100 certification strengthens RLC's competitive position and standardizes quality, reliability and safety processes across its aerospace programs, and reflects RLC's commitment to meeting and exceeding the increasingly stringent industry requirements for aerospace related products.

For More Information

For up-to-date news briefs, visit mwjournal.com.


SYNERGY
MICROWAVE CORPORATION

Around the **Circuit**

Bonding Source, a provider of microelectronics manufacturing material and equipment based in Manchester N.H., donated $8,500 worth of equipment and supplies to support the microelectronics manufacturing program at Nashua Community College. The company also provided funds for employees to make a donation to the organization of their choice. YMCA Camp MiTeNa, Bedford Memorial School, FIRST, Hope for Recovery and HAVEN NH each received a $750.00 donation.

Rugged data storage experts at **Phoenix International** in Orange, Calif., have received a gold award in the 2016 Military & Aerospace Electronics and Intelligent Aerospace Technology Innovation Awards for the company's rugged RPC24 Raid Array data storage system. The award to the Phoenix RPC24 data storage system is part of the middle of three tiers of this year's Technology Innovation Awards. The top award level is platinum, the middle tier is gold and the third tier is silver. Military & Aerospace Electronics and Intelligent Aerospace awarded company entries that offer solutions to difficult aerospace and defense electronics design challenges.

CONTRACTS

CACI International Inc. announced it was awarded a $140 million prime contract to provide global logistics support services for the **United States Fleet Forces Command (USFFC) Naval Forces Logistics (NFL) Support/Training Services** program. The five-year contract represents continuing business in CACI's Logistics and Material Readiness market area. USFFC supports the Chief of Naval Operations and Combat Commanders worldwide by providing responsive, relevant, sustainable Naval Operating Forces that are ready for continual combat operations. The command is responsible for organizing, manning, training, equipping, and maintaining Naval forces to generate required and sustainable levels of current and future readiness.

The **U.S. Air Force** has approved **Lockheed Martin's** design to upgrade the current GPS satellite ground control system with new capabilities that will enable it to operate more powerful and accurate GPS III satellites. The successful Critical Design Review (CDR) for the Contingency Operations (COps) contract, gives Lockheed Martin a green light to proceed with software development and systems engineering to modify the existing GPS ground control system, called the Architecture Evolution Plan (AEP) Operational Control Segment. The Air Force awarded the $96 million COps services and supplies contract to Lockheed Martin on February 3, 2016.

Anaren Inc. announced that its subsidiary, **Unicircuit**, has been selected by **Lockheed Martin** to receive orders in excess of $40 million for microwave assemblies in support of the Long Range Discrimination Radar (LRDR) system. The radar system will support a layered ballistic missile defense strategy to protect the U.S. homeland from ballistic missile attacks. Work will begin immediately and is expected to be completed in the fourth quarter of calendar year 2018. Production will be shared between Unicircuit (80%) and Anaren's East Syracuse NY (20%) facilities. Anaren's Unicircuit facility, located in Littleton Colo., provides high-reliability, high-density printed circuit board and integrated assembly solutions for use in aerospace and defense markets.

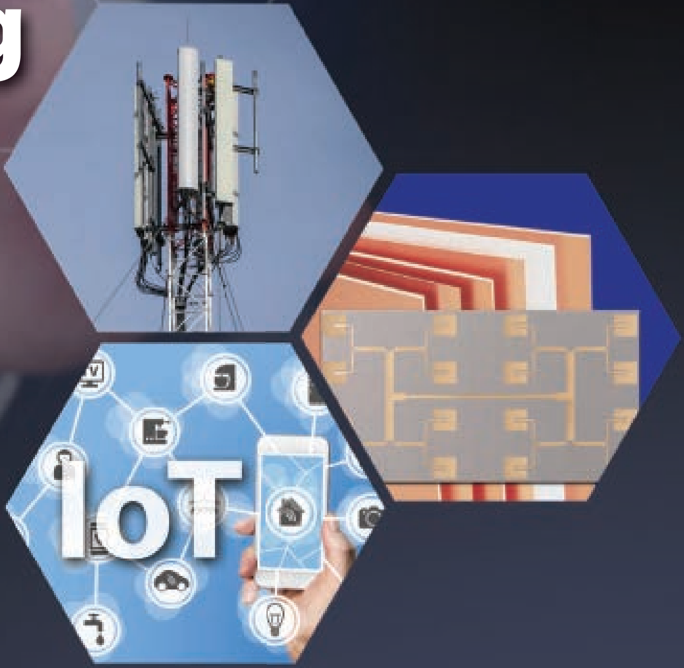
Raytheon has won a $37 million contract from the **U.S. Air Force** to demonstrate new satellite communications technology that will continuously link tactical users with military leaders in contested environments. Managed by the Space and Missile Systems Center at Los Angeles Air Force Base, the Protected Tactical Services Field Demonstration, or PTSFD program represents a major improvement in anti-jam security via the Wideband Global Satellite Communications (WGS) constellation and commercial satellites. Eventually, hardware developed and tested under the PTSFD contract can be deployed as upgrades to existing satellite communication terminals.

Engility Holdings Inc. announced it was awarded a $31 million contract to provide cyber security assessment, analysis and research for the **Defense Technical Information Center (DTIC)** in support of the Air Force Life Cycle Management Center, Cyber Security Engineering Division. Engility will deliver cutting-edge cyber services and solutions that include assessments, independent verification and validation (IV&V), site audits, software assurance, prototypes and processes. The company will study, analyze, advise and conduct research and development to advance cyber security for Air Force mission requirements. Engility's approach to penetration testing of security requirements is anticipated to save the program substantial time and cost.

Mercury Systems Inc. announced that it received a $10.8 million follow-on order against its five year sole source basic ordering agreement (BOA) to deliver advanced Digital RF Memory (DRFM) jammers to the **U.S. Navy**. The order was received in the company's fiscal 2017 second quarter and is expected to be shipped over the next several quarters.

Antenna Systems Solutions S.L. (Celestia Technologies Group), a provider of antenna measurement solutions for the defence, government and wireless industries, announced that it has won a contract to supply a Compact Antenna Test Range (CATR) with a 2m quiet zone to **Russian Systems and Technology** in Moscow, Russia. The system will operate from 1 to 40 GHz and will be used to measure point-to-point microwave antennas.

Forward Thinking



Introducing RO4730G3™ 94 V-0 Laminates: For Tomorrow's Wireless PCB Antennas

Rogers RO4730G3™ circuit laminates have been engineered for next-generation wireless PCB antennas, including in 4G and 5G cellular base stations and IoT networks.

These low-loss, cost-effective circuit materials are lead-free process compatible and flame retardant. RO4730G3 laminates support broadband antenna designs with excellent PIM performance, outstanding dimensional stability and multilayer board design capability.

Built on the proven technology used in Rogers RO4000® thermoset resin/ceramic/woven glass materials, RO4730G3 94 V-0 laminates expand Rogers antenna grade product family, already the most popular for base station antennas.
For tomorrow's PCB antennas today — RO4730G3 Laminates

MATERIAL	Dk	PIM*
RO4730G3 Ceramic Hydrocarbon	**3.0**	**<-160 dBc**
RO4700JXR™ Series Ceramic Hydrocarbon	2.55 to 3.0	<-160 dBc
RO4500™ Series Ceramic Hydrocarbon	3.3 to 3.5	<-157 dBc
AD Series™ PTFE	2.5 to 3.2	<-157 dBc

** On 0.060" (1.524mm) laminate*

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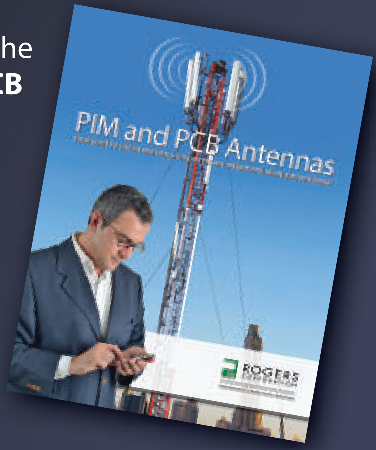
Brochure



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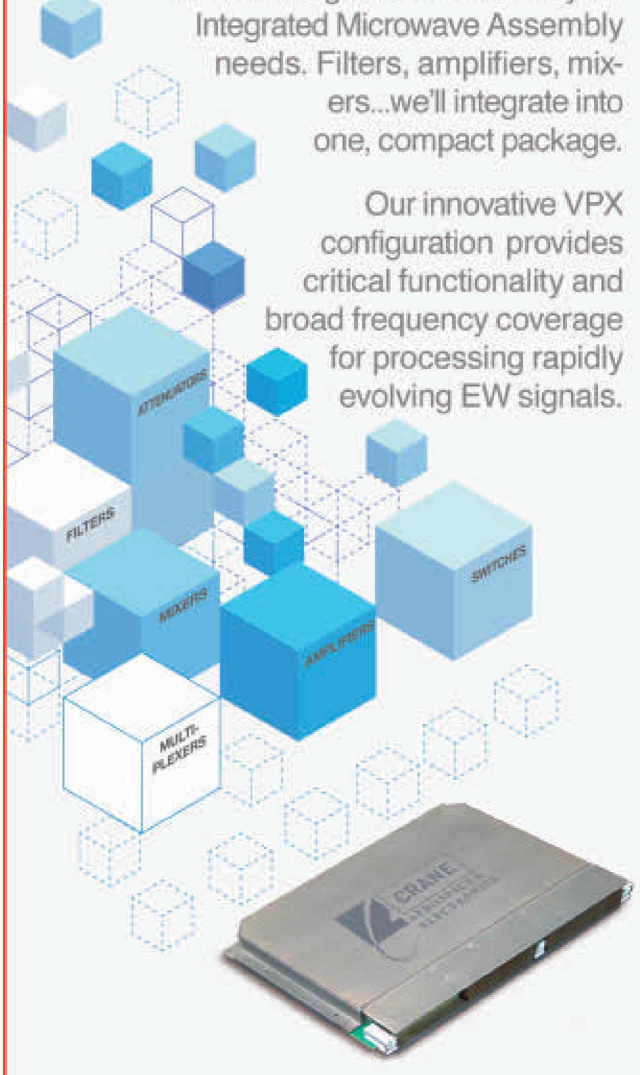


Around the **Circuit**

PEOPLE

▲ *Christopher F. Marki*

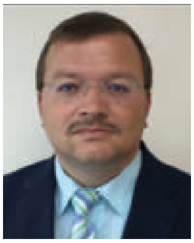
After 25 years of stable management structure, **Marki Microwave** announced the first ever change in executive leadership. **Christopher F. Marki,** Ph.D. has assumed the role of chief executive officer, while **Ferenc Marki** will remain as president of the company.

▲ *Tom Barron*

Delta Electronics Mfg. Corp. welcomed **Tom Barron** as new market and new product development manager. Barron has spent over 25 years marketing RF/microwave and multi-pin interconnect solutions within the medical, mil/aero, telecom, data infrastructure, broadcast and test & measurement markets. Before joining Delta Electronics Mfg. Corp., Barron was global director of sales for a $100 million+ connector manufacturer, where he led a team of regional sales managers and a network of manufacturers' representatives. Prior to that endeavor, Barron founded and successfully managed a manufacturers' representative firm, Uplink International Inc., and a prototype cable assembly company, Red Pillar Inc.

▲ *Susan L. Spradley*

Qorvo®, a provider of innovative RF solutions that connect the world, announced the election of **Susan L. Spradley** to its board of directors, effective January 1, 2017. Spradley will also join the board's governance and nominating committee. Spradley has substantial senior management experience in the communications industry, most recently as executive vice president and general manager – network and service enablement for Viavi Solutions (formerly JDS Uniphase). Previously, she served in a variety of leadership positions with global telecommunications companies, including Nokia Siemens Networks and Nortel, and was a member of the board of directors of EXFO Inc., a provider of test and service assurance solutions for communications network operators and OEMs.



▲ *Andreas Karch*

Indium Corp.'s Andreas Karch, regional Technical Manager for Germany, Austria and Switzerland, was recognized for his technical presentation at the IMAPS Autumn Conference in October in Munich, Germany. Karch was awarded "Best Presentation" for the session, "New Solder Material Technology in the Manufacturing Process of IGBT Modules," which discussed a new method that produces strong, reliable solder joints that resist cracking and thermal fatigue.

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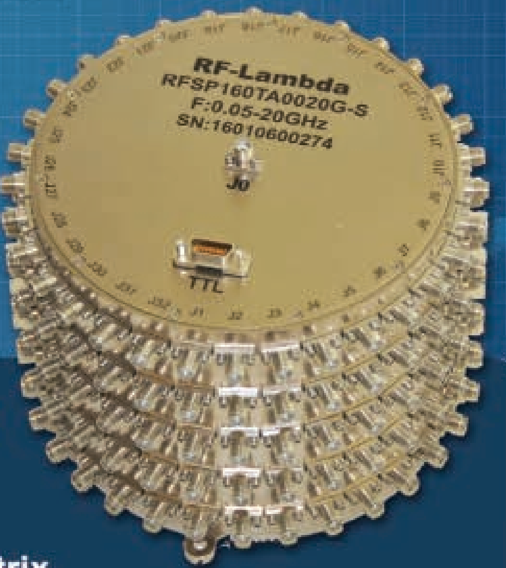

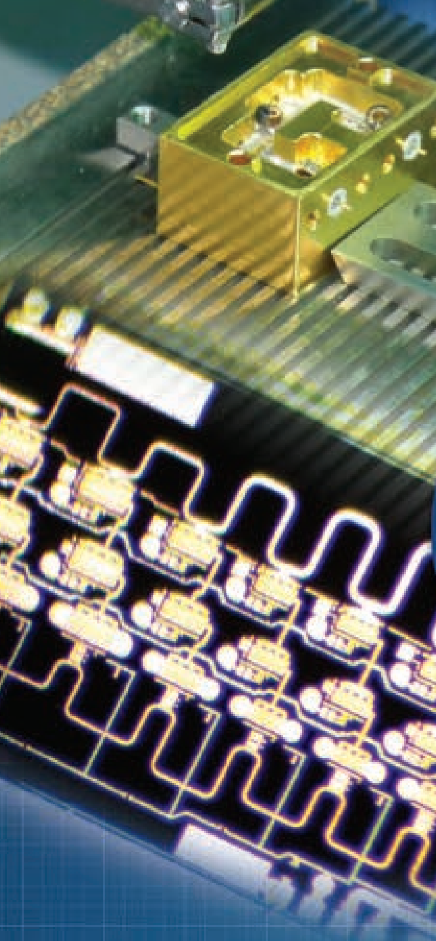

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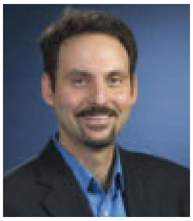
Around the **Circuit**

Karch provides support, including sharing process knowledge and making technical recommendations for the use of Indium Corp.'s materials, including solder paste, solder preforms, fluxes, and thermal management materials. Karch has more than 20 years of automotive industry experience, including the advanced development of customized electronics.

Worcester Polytechnic Institute (WPI) electrical and computer engineering professor **Alex Wyglinski** has received an ORB Analytics award for his work, "A High-Speed Variable Rate PSK Satellite Modem." This award involved the development of a high-speed variable rate Phase Shift Keying (PSK) satellite modem whose functionality is suitable for implementation on an FPGA. This award also leverages the satellite communications in-house expertise at Professor Wyglinski's Wireless Innovation Laboratory (WILab), an internationally recognized facility conducting fundamental and applied research in the areas of wireless communications, software-defined radio, vehicular communications, cognitive radio, satellite transmission and vehicular technology. Wyglinski and his WILab were recently profiled in *Microwave Journal*'s November 2016 Fabs & Labs column.


▲ *Alex Wyglinski*

REP APPOINTMENTS

Anokiwave Inc., a provider of highly integrated IC solutions for mmWave markets and active antenna based solutions, announced that they have signed a representative agreement with **JS Commtech** in South Korea. The agreement aligns with Anokiwave's goal to support new customers and opportunities for our highly-integrated active antenna core IC solutions in South Korea. JS Commtech has a highly technical sales and engineering staff and is a well-respected representative in Korea for all RF/microwave, commercial and defense related markets.

Ardent Concepts introduced their new manufacturer's representatives that they've appointed to the west coast territory. **Tech Coast Sales**, **RF Microwaves Sales & Marketing LLC** and **Sea-Port Technical Sales Inc.** bring excellent technical knowledge and experience to their sales channel.

Integrated Device Technology Inc. announced that it has signed a global franchise agreement with **Future Electronics**. Under the agreement, Montreal-based Future Electronics becomes IDT's newest distributor of products through its offices in 44 countries spanning the globe.

The Wireless Telecom Group has signed an agreement with **AR Europe** for the distribution of Boonton

Planar Monolithics Industries, Inc.

High Power Solid-State Switches

- **Amplifiers – Solid State**
- **Attenuators – Variable/ Programmable**
- **Couplers (Quadrature, 180° & Directional)**
- **Detectors – RF/Microwave**
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- **Miscellaneous Products**
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- **Pulse Modulators (SPST)**
- **Rack & Chassis Mount Products**
- **Receiver Front Ends & Transceivers**
- **SDLVAs, ERDLVAs & DLVAs**
- **Single Side Band Modulators**
- **SMT & QFN Products**
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- **Systems – Fly Eye Radars**
- **Threshold Detectors**
- **USB Products**

PMI offers a full line of High Power Solid-State Switches that range from DC to 18 GHz with power handling up to 130 Watts CW, 5 kW peak. A wide range of standard models with various options are available.

Model: P2T-1G18G-10-R-528-SFF-HIP10W

http://www.pmi-rf.com/Products/Switches/P2T-1G18G-10-R-528-SFF-HIP10W.htm

Frequency	0.1 to 18.0 GHz
Isolation	25 dB Min - Measured 25.73 dB
VSWR	2.0:1 Max - Measured 1.76:1
Insertion Loss	3.5 dB Max - Measured 2.66 dB
RF Input Power	10 Watts CW Max - Tested at 10 W CW
Switching Speed	200 ns Max - Measured 60 ns
Temperature	-54 °C to +100 °C

Package Size:
1.2” x 1.0” x 0.5”
Connectors: SMA (F)
DC Voltage:
+5 VDC @ 3.0 mA
-28 VDC @ 3.0 mA

Model: P2T-6G18G-40-R-570-TFF-1D6KW

http://www.pmi-rf.com/Products/switches/P2T-6G18G-40-R-570-TFF-1D6KW.htm

Frequency	6.0 to 18.0 GHz
Isolation	40 dB Min - Measured 40 dB
VSWR	2.0:1 Max - Measured 1.99:1
Insertion Loss	2.2 dB Max - Measured 2.04 dB
RF Input Power	100 Watts CW / 1.6 KW Peak - Tested to 130 Watts CW
Switching Speed	200 ns Max - Measured 165 ns
Temperature	-40 °C to +85 °C

Package Size:
2.00” sq X 0.50”
Connectors: TNC (F)
DC Voltage:
+5 VDC @ 265 mA
-70 VDC @ 17 mA

Model: P2T-1G1R1G-25-R-SFF-100W-SM

http://www.pmi-rf.com/Products/switches/P2T-1G1R1G-25-R-SFF-100W-SM.htm

Frequency	1.0 to 1.1 GHz
Isolation	25 dB Min - Measured 40.26 dB
VSWR	1.5:1 Max - Measured 1.2:1
Insertion Loss	0.8 dB Max - Measured 0.32 dB
RF Input Power	100 Watts CW / 5 kW Peak - Tested to 100 W CW
Switching Speed	250 ns Typ - Measured 310 ns Max
Temperature	-45 °C to +85 °C

Package Size:
3.25” x 2.75” x 0.70”
Connectors: TNC (F)
DC Voltage:
+5 VDC @ 128 mA
+50 VDC @ 10 mA

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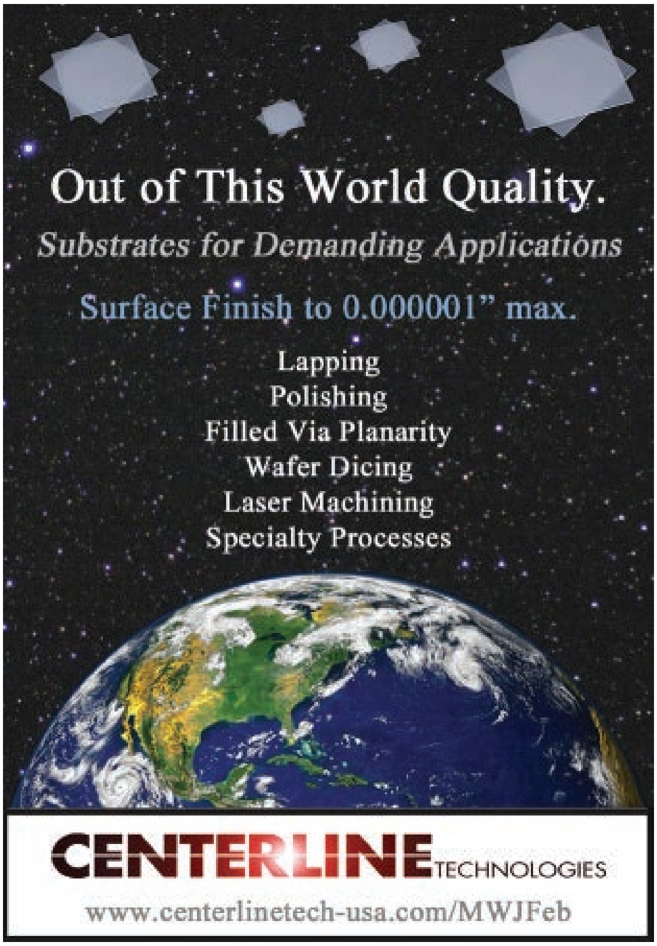
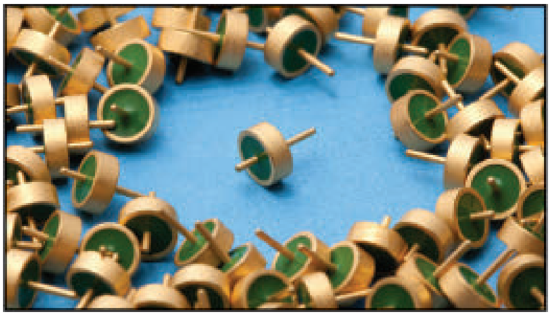




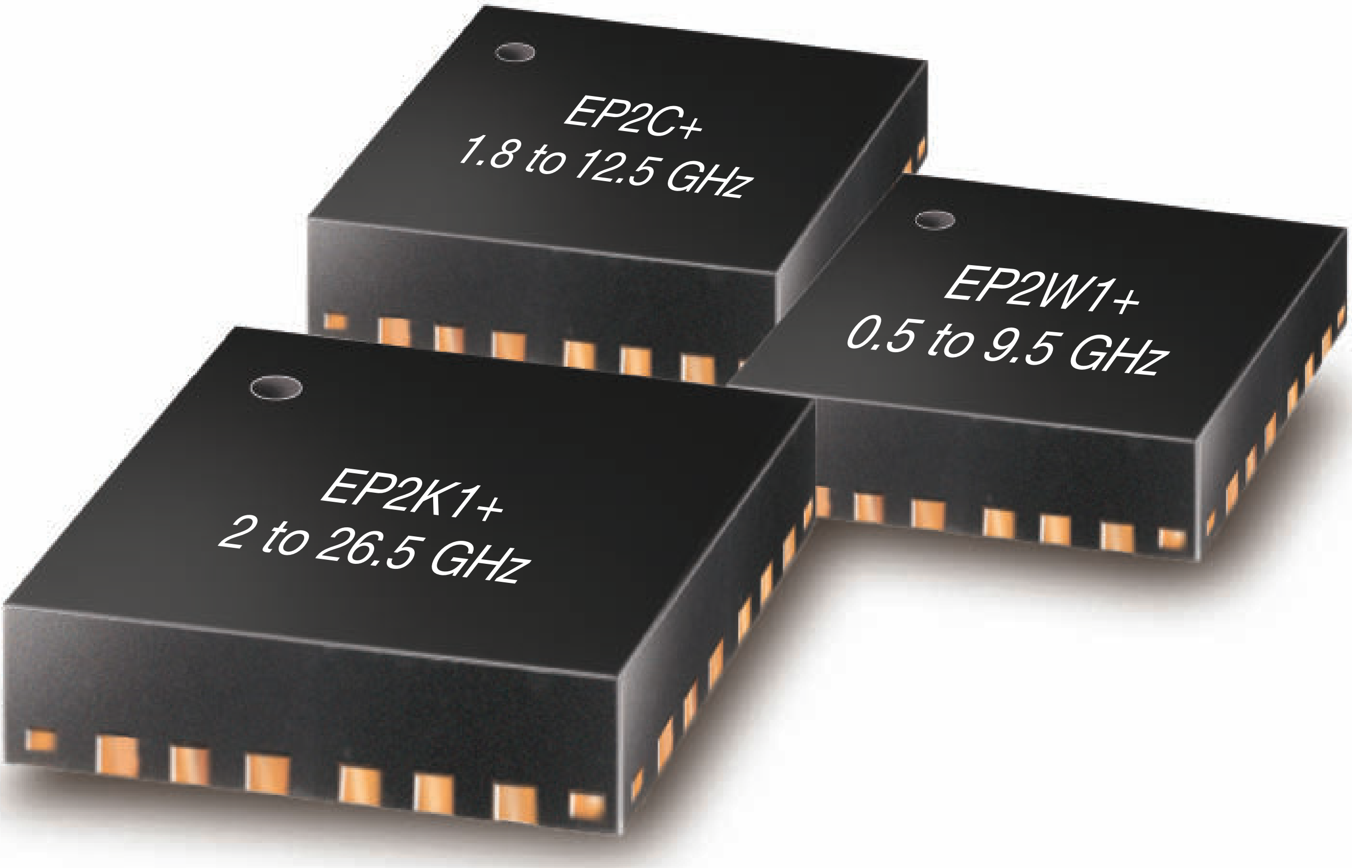
Around the **Circuit**

Electronics and Noisecom products throughout Europe. AR Europe's RF expertise and instrumentation experience along with their sales and distribution reach will place Boonton RF power meters, sensors, meters and analyzers along with Noisecom noise generation components, modules and instruments in front of design and test engineers, system integrators and field service technicians across Europe. Wireless Telecom Group is committed to working with AR Europe to provide the highest quality customer service, technical support and RF instrumentation solutions.

PLACES

MACOM Technology Solutions Inc. has opened a new EMEA Centre of Excellence focused on its activity in GaN and silicon germanium (SiGe) technology, targeted at RF energy, aerospace and defense and beamformer applications. The local team will provide product design, marketing and program management capabilities. The new premises are located directly at the Novio Tech Campus in Nijmegen, the Netherlands. This historical city makes it very easy for customers to meet with MACOM face-to-face as it can be reached by a direct train connection from Amsterdam Airport Schiphol.

BAE Systems has opened the £15.6 million Academy for Skills & Knowledge (ASK) training academy that will train all the apprentices and graduates in the company's military aircraft business as well as providing life-long learning and skills development activities for 13,000 employees for at least the next four decades. The 7,400 m^2 ASK, which is situated on the Samlesbury Aerospace Enterprise Zone in Lancashire, UK alongside BAE Systems' military aircraft advanced manufacturing centre, will also act as a collaborative skills-hub for the North West of England's engineering and manufacturing sector and offer an exciting learning education centre for school children from five to 14 years old.


EP2C+
1.8 to 12.5 GHz
EP2W1+
0.5 to 9.5 GHz
EP2K1+
2 to 26.5 GHz

Millimeter Wave Active Bandpass Filters

Saurabh Chaturvedi, Mladen Božanic and Saurabh Sinha
University of Johannesburg, Johannesburg, South Africa

A review of millimeter wave (mmWave) active bandpass filters (BPF) is presented to motivate research and development of high performance mmWave BPFs, especially above 60 GHz. Active BPFs exhibit the merits of low loss, good out-of-band rejection, good selectivity and a high integration level. The details of various design approaches and realization techniques are provided. Their strengths, weaknesses and design challenges are discussed.

The mmWave spectrum spans the frequency range from 30 to 300 GHz. It offers various unlicensed frequency bands and supports gigabits/second (Gbps) wireless communication. At around 60 GHz, the unlicensed frequency bands of 57 to 64 GHz in the U.S. and Korea, 59 to 66 GHz in Japan and Europe, 59.4 to 62.9 GHz in Australia and 59 to 64 GHz in South Africa are available. Free-space path loss, mmWave absorption by atmospheric oxygen and water vapour, rain attenuation, losses in building materials and absorption by floors and walls affect and limit propagation. These effects make the 60 GHz band more suitable for short distance (less than 1 km) communications.

Electronic filters are used to allow the desirable frequency components and to reject the unwanted components of a signal. A bandpass filter (BPF) passes the frequencies within a specified range and attenuates other frequency components. A BPF is located between the antenna and the low noise amplifier (LNA) in the RF receiver of a communication system.

BPFs can be divided into three types, including purely active, purely passive and active (active + passive or semi-passive).[1] In purely passive (passive) filters, only passive components, i.e., resistors, capacitors and inductors are used. These filters do not have the capability of signal amplification. A power supply is not required for the operation of passive filters, therefore, they do not dissipate power. Since these filters do not consist of active devices, there is no active noise. They generate only thermal noise because of the resistive components. Consequently, passive filters demonstrate better noise performance. In purely active and active (semi-passive) filters, transistors are used as active components, therefore, these filters exhibit operating frequency limitations, poor linearity and high noise figure (NF) and power dissipation. They do, however, require less area than that of passive filters.

Passive filters suffer from high loss. They also have the shortcomings of incompatibility with tunable elements, they require tradeoffs between bandwidth (BW) and insertion loss (IL) and they have low out-of-band rejection levels. No complementary metal oxide semiconductor (CMOS) passive BPF with 3 dB fractional bandwidth (FBW) below 10 percent or above 65 percent has been reported.

Active filters are realized by applying loss compensation (Q-enhancement) techniques, and can be used in transceiver modules to reduce loss and size.[2] CMOS active BPFs that have 3 dB FBWs less than 10 percent with low IL have been reported.[3,4] Loss compensation techniques can reduce IL to 0 dB.[3,5,6] Moreover, good out-of-band rejection can be achieved at low as well as high frequencies. Besides the advantages of small size and low loss, active monolithic filters also have the qualities of good selectivity, a high level of integration with other circuits, and an electronic tuning capability.

Traditionally, gallium arsenide (GaAs) and indium phosphide (InP) (III-V technologies) have been assumed to be the only appro-

priate options for mmWave circuit implementation because of the high speed of devices using these technologies. III-V heterojunction bipolar transistor (HBT) and high electron mobility transistor (HEMT) technologies offer high cutoff frequencies (f_T). GaAs and InP substrates show semi-insulating characteristics, with high resistivity in the order of 10^7 to 10^9 Ω-cm. However, III-V technologies exhibit the drawbacks of low thermal conductivity (0.46 W/cm-K for GaAs and 0.68 for InP at 300K, while silicon (Si) is 1.41), high leakage current, device reliability issues, a low integration level and high cost.

The CMOS process demonstrates low cost, a level of high integration and high reliability. MOS field effect transistor (MOSFET) scaling has supported the production of high speed transistors in CMOS technology. Nevertheless, low Q-factors of on-chip passives and poor noise performance are the major drawbacks of CMOS process.

Besides CMOS, silicon germanium bipolar CMOS (SiGe BiCMOS) is another prominent Si technology used in RF and mmWave circuit design. A SiGe HBT offers higher gain and better noise and power performance than a Si bipolar junction transistor (BJT). The performance of the SiGe BiCMOS process is competitive with GaAs and InP processes. The strength of SiGe technology is the ability to use the CMOS process for the fabrication of digital, analog and RF modules on a single chip. This is not available with any other technologies (e.g., GaAs, InP).

ACTIVE BPF DESIGN APPROACHES

Various approaches to active BPF design have been reported, some of which include transversal, recursive, cascade connections of passive filters with amplifiers, active matching, active inverter, negative capacitance and negative resistance. Of all these approaches, the negative resistance technique is the simplest and most appropriate for mmWave active filter design.[2] This topology can be used in both lumped and distributed resonators. Negative resistance is used to increase the Q-factor of the passive network through resistive loss compensation. This approach makes active filters more stable, while also exhibiting good rejection ratios.[7] The negative resistance topologies include transformer feedback, tapped-inductor feedback, active capacitance, active device reduction, cross-coupled pair, and others.

Figure 1 illustrates a resonator made of a quarter-wavelength (λ/4) transmission line (TL). The short circuited port of the resonator is replaced with a negative resistance ($-R_N$) for resonator loss compensation. The expression for

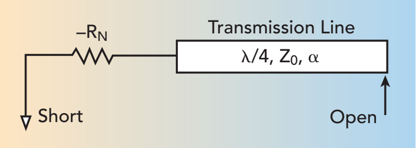


Fig. 1 Loss compensation with negative resistance.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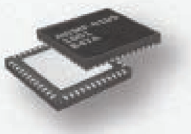


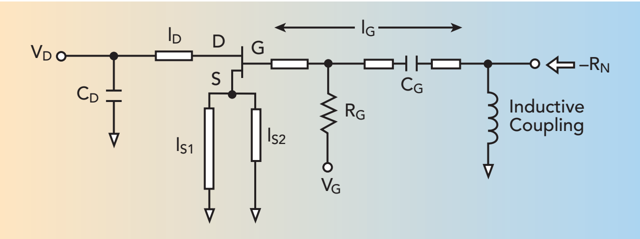
loss as a function of attenuation constant (α) of the TL is represented by Equation 1. Equation 2 expresses the gain generated by the negative resistance in terms of line characteristic impedance (Z_0) and R_N. When Equation 3 is satisfied, loss of the resonator is completely compensated, and its Q-factor becomes infinite. For this condition, R_N is represented by Equation 4. If the value of R_N is greater than that provided by Equation 4, the resonator holds a loop-gain, and oscillation arises.[2]

$$\text{Loss} = e^{-\lambda\alpha/2} \qquad (1)$$

$$\text{Gain} = \frac{-R_N - Z_0}{-R_N + Z_0} \qquad (2)$$

$$\text{Loss} \times \text{Gain} = 1 \qquad (3)$$

$$R_N = \frac{Z_0\left(e^{\lambda\alpha/2} - 1\right)}{e^{\lambda\alpha/2} + 1} \qquad (4)$$



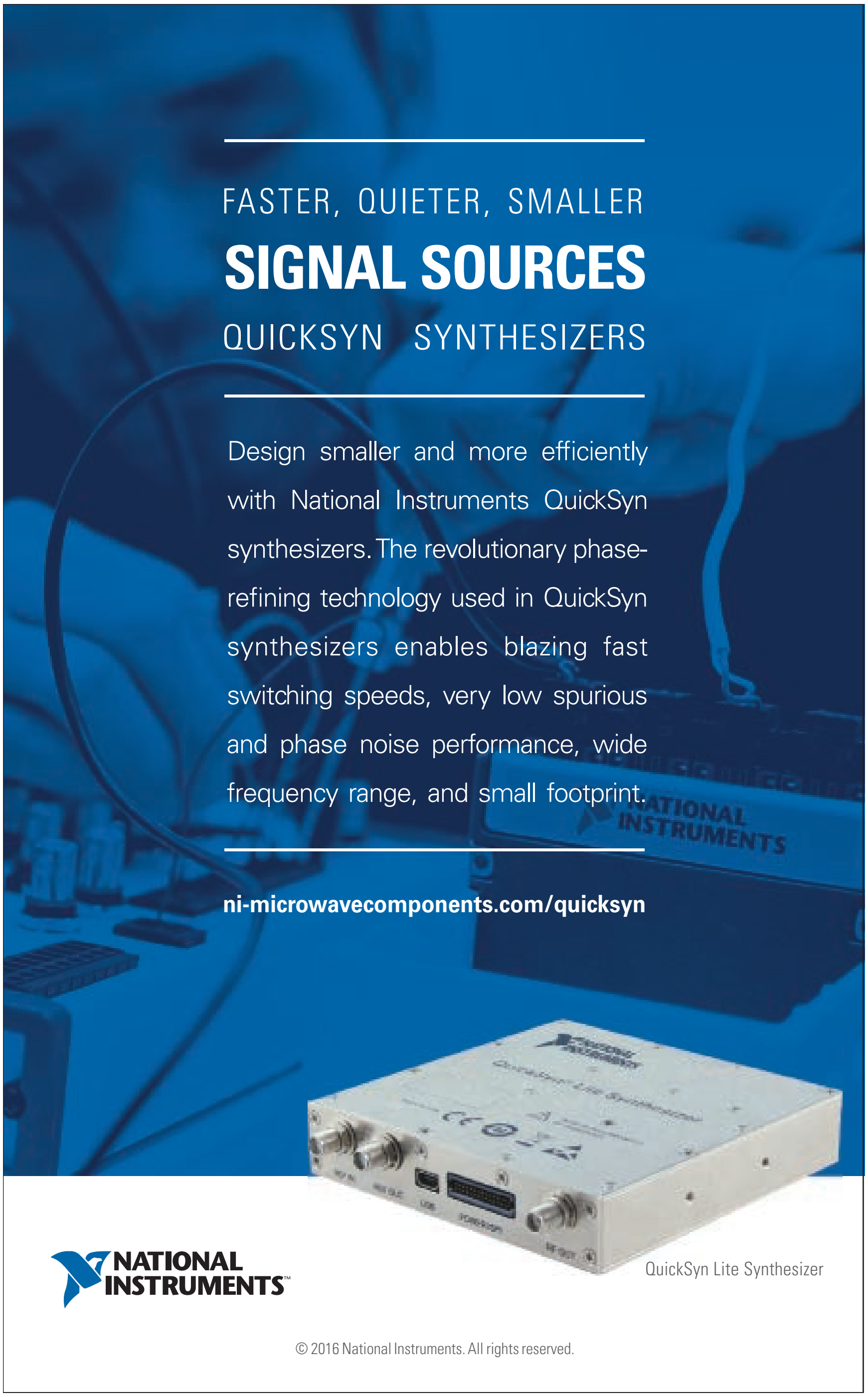
Besides satisfying Equation 4, negative resistance should be constant over a broad frequency range to compensate the loss of a passive resonator without causing oscillation and instability. ***Figure 2*** shows the negative resistance circuit with a FET as an active component, and ***Figure 3*** is a schematic of a two-stage active BPF using the negative resistance technique.

ACTIVE BPF REALIZATION TECHNIQUES

Active BPFs can be broadly classified into two categories: Q-enhanced non-TL based and Q-enhanced TL based. The Q-enhanced non-TL based technique can be further divided into two parts: LC based and active capacitance based.

Q-enhanced LC based active BPFs use mainly transformer feedback[8,9] and tapped-inductor feedback[10] architectures. The tapped-inductor feedback technique provides high inductance, low power dissipation and small size compared to the conventional transformer feedback topology. Nonetheless, active BPFs realized with both of these topologies have the disadvantages of relatively high NF and high power consumption. These topologies generally use common-source or common-gate series feedback structures, which are mostly employed in oscillator circuit design. Owing to the series feedback structure, the noise performance of these active BPFs is degraded.[1]

In low GHz (less than 10 GHz) RF integrated circuit (IC) design, the main challenge is the low Q-factors of on-chip passive inductors. The IL of active BPFs at these frequencies is mostly governed by the low Q of these inductors. At mmWave



frequencies, passive inductors show desirable Q-factors of 15 or more. The Q-factors of on-chip passive inductors increase with increasing frequency, while those of on-chip passive capacitors tend to decrease. Therefore, in mmWave filters, the IL is affected mainly by the Q-factors of the capacitors. The NF also depends on IL, so both IL and NF can be reduced by using high-Q capacitors in active filter design.[11] Furthermore, with increasing frequency, capacitances of on-chip passive capacitors also increase. Low Q-factors and deviation in capacitance values with frequency are serious drawbacks. Consequently, the overall performance of mmWave ICs is significantly degraded.

On-chip active capacitors are better substitutes for on-chip passive capacitors. Active capacitors are constructed with transistors and possess high Q-factors and tunable capabilities. These high-Q capacitors can be used for loss and noise performance improvement of mmWave active BPFs. Q-enhanced LC based active BPFs suffer from poor noise and power performance, while BPFs realized with active capacitors do not.[1,11]

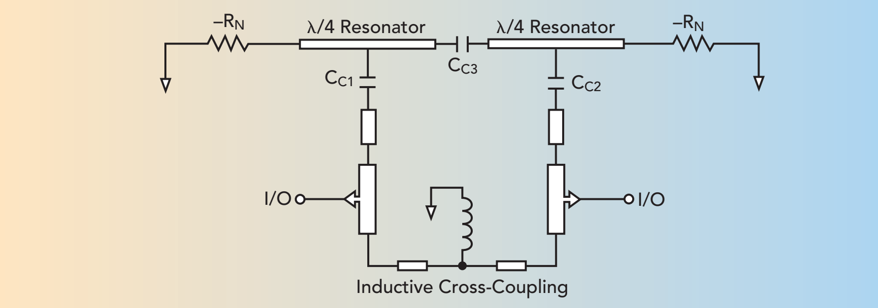


Fig. 3 Two stage active BPF with negative resistance.

Active BPFs have been reported that use Q-enhanced TL based techniques, such as cross-coupled pair,[3-5,12] and coupled negative resistance.[13] Different cross-coupled pair architectures are applied to the resonator to compensate for the resistive losses, including nMOS[5,12,14] and complementary[3,4] cross-coupled pair.

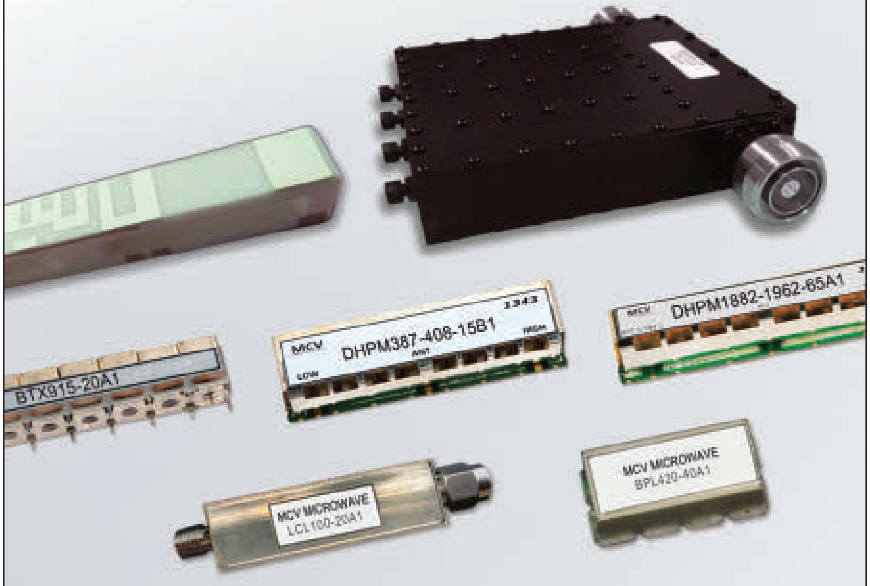
The realization of passive resonators using synthetic quasi-transverse electromagnetic (quasi-TEM) TLs, also known as complementary conducting strip TLs (CCS TL), has been reported.[3,4] Compared to conventional thin-film microstrip line, CCS TL can provide more parameters

TABLE 1

PERFORMANCE COMPARISON OF ACTIVE BANDPASS FILTERS

Ref.	Process	N	f_c (GHz)	3 dB BW (percent)	P_{DC} (mW)	NF (dB)	P_{1dB} (dBm)	Chip Area (mm^2)	IL (dB)	RL (dB)	FOM (dB)
8	0.18 µm CMOS	4	2.03	6.5	16.6	15	-6.6	1.21	0	10	77
6	0.25 µm CMOS	3	2.14	2.8	17.5	18.9	-13.4	3.51	0	12	68.9
9	0.18 µm CMOS	3	2.36	2.53	8.8	19	-20	2.25	1.8	11.5	66
7	0.15 µm GaAs	2	22.6	4	50.4	17	-19	1	8	7.7	67.5
5	0.18 µm CMOS	2	34.2	18.8	3.7	7*	-4.6	0.12**	0	14.6	98.3
4	0.18 µm CMOS	2	22.7	7.39	3.3	14.1	-7.7	0.13**	0.15	9.96	91
10	0.18 µm CMOS	2	23.5	17	4.2	6.7	-3.5	0.37	1.65	13.2	98
17	0.18 µm CMOS	2	2.44	2.46	10.8	18	-15	0.53	6	19	70
14	0.18 µm CMOS	2	6.02	18.94	5.4	12	-15.2	1.08	2.2	7.64	73.5
12	0.18 µm CMOS	3	1.58	8.0	14.4	15	-13.83	0.92	0.68	16	67.6
3	0.13 µm CMOS	2	24.1	3.86	5.4	14.1	-25.43	0.073**	0	13.3	74
1	0.18 µm CMOS	2	5.3	32	2.2	4.3	2.5	0.7	0.77	18	100
2	0.15 µm GaAs	2	65	4	-	10.5	-	2.75	3	9.4	-
2	0.15 µm GaAs	2	65	2	-	-	5	2.75	2.8	9.1	-

*Simulated results ** Without test pads



for synthesis without any changes in the process and material constants. In addition, a CCS TL can be meandered in a 2-D plane with fewer coupling effects. Efficiently meandered CCS TLs can provide compact layouts, size miniaturization, and a high degree of integration. All of these attractive features of CCS TL support its application in monolithic microwave integrated circuits (MMIC) and system on chip (SOC) implementation.

A modified form of the CCS TL, known as a condensed complementary conducting strip TL (C-CCS TL) has been described for passive resonator realization.[12] The C-CCS TL has a significant capability for further area reduction. Both the CCS TL and C-CCS TL facilitate size reduction and Q-factor improvement simultaneously and may, therefore, be selected for TL based compact mmWave BPF design.

SELECTIVITY AND MULTIMODE

The selectivity of low order on-chip BPFs is unsatisfactory.[10] Conventional second-order BPFs show low out-of-band rejection levels. The selectivity of a filter can be improved by increasing its order, at the expense of increased IL and chip area. Various highly selective active BPFs are reported using the concept of transmission zeros. These transmission zeros are placed on either side of the filter passband.

Most on-chip BPFs have been designed using singlemode resonators. The size and loss of a filter can be reduced by modifying the conventional resonator to generate additional modes for the realization of multimode operation.[15] A SiGe BiCMOS on-chip multimode passive BPF based on a multimode resonator (MMR) is reported by Ma et al.[15] It exhibits low IL in a small chip area. Dualmode BPFs have achieved great importance in advanced wireless communication systems because of their high Q-factors, good selectivity and narrowband performance. The dualmode active BPF was first reported by Karacaoglu et al.[16] A ring resonator based dualmode CMOS active BPF using CCS TLs is presented by Su and Tzuang.[3]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PERFORMANCE COMPARISON

The performance parameters of previously reported active BPFs[1,3,5,8,10,17] are compared in *Table 1*. N, f_c, P_{DC}, P_{1dB} and RL are the order (number of poles), center frequency, DC power dissipation, in-band input 1 dB compression point, and return loss, respectively, of a BPF. Figure of merit (FOM) is a parameter used to compare active RF BPFs and is defined as:[8,10]

$$\mathrm{FOM_{dB}} = 10\log\left(\frac{N\times P_{1dB}\times f_c}{FBW\times P_{DC}\times NF}\right) \quad (5)$$

where P_{DC} and P_{1dB} are in watts, f_c is in Hz, and NF and FBW are actual values (not converted to dB and percentage, respectively).

WEAKNESSES OF ACTIVE BPFs

Weaknesses of active filters include high NF, operating frequency limitations and sensitivity to process variations as well as environmental conditions. Very few active BPFs are implemented at mmWave frequencies. The center frequencies of those reported include 31.8 GHz in GaAs,[18] 34.2 GHz in CMOS process,[5] 40 GHz in CMOS[11] and 65 GHz in GaAs.[2] Reducing the NF and increasing the operating frequency of active BPFs are major design challenges.

CONCLUSION

This article provides a comprehensive review of mmWave active BPFs. On-chip active BPFs have the main disadvantages of high NF and moderate operating frequency. To the best of the authors' knowledge, only one research article[2] has reported active BPFs with center frequencies around and above 60 GHz, and these filters are implemented in GaAs process. The performance and feasibility of the CMOS process for the design of such high frequency active filters need further investigation. While CMOS RF circuits face the problem of poor noise performance, the SiGe BiCMOS process may be an appropriate alternative.■

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Editor's note: The authors' biographies were printed with their prior article, "Millimeter Wave Passive Bandpass Filters," published in the January 2017 issue.

Erratum

In the companion article, "Millimeter Wave Passive Bandpass Filters," published in the January 2017 issue, Equation 4 should be

$$Q_C = \frac{\omega_0 C}{G}$$

Also, on page 102, T_L in the top paragraph of the right-hand column should be TL, for transmission line.

60 GHz CMOS Circular Patch Antenna-on-Chip

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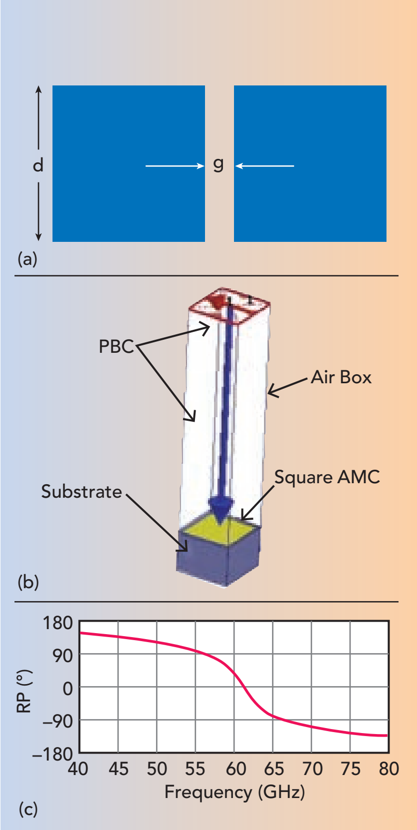
Egypt-Japan University of Science and Technology
Hala Elsadek
Electronics Research Institute
Ramesh K. Pokharel
Kyushu University
Aimeric Bisognin
University Nice-Sophia Antipolis and ST Microelectronics
Cyril Luxey
University Nice-Sophia Antipolis and Institut Universitaire de France

This article presents a 60 GHz circular patch Antenna-on-Chip (AoC) on asymmetric Artificial Magnetic Conductor (AMC) designed and fabricated using the TSMC 0.18 μm CMOS process. An AMC plane allows a positive reflection coefficient within the bandwidth of interest so incident and reflected waves are in phase. At the AMC frequency of operation, a high impedance is generated which reduces surface waves and thus enhances gain. At first, circular AoC performance is enhanced using a square AMC. However, square AMC cells suffer from discontinuities that affect performance when using lengthy feed lines to connect the AoC to a front-end circuit. To overcome this problem, an asymmetric rectangular (R-AMC) is employed. A modified asymmetric AMC is used with a circular AoC for further gain enhancement. The area of the fabricated design is only 1715 μm x 710 μm. Measured $|S_{11}|$, gain and radiation patterns are reported.

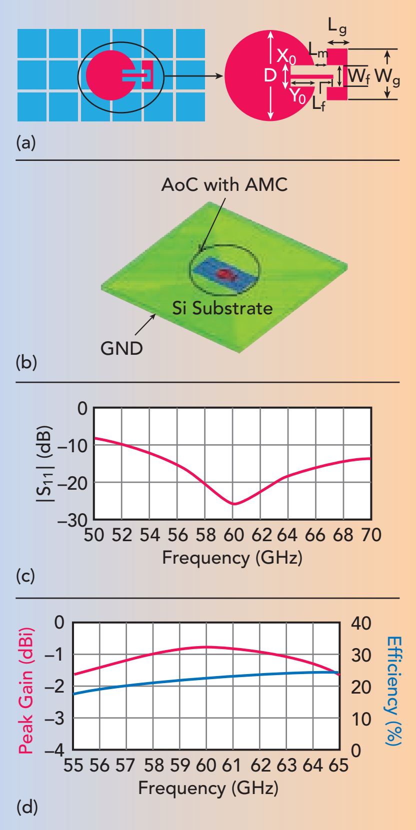
The 60 GHz Band has an unlicensed bandwidth of 7 GHz (from 57 to 64 GHz), which allows for a high data rate of several gigabytes/sec, surpassing the capability of current wireless technologies. The exploitation of this frequency band is of interest for a variety of emerging applications such as uncompressed high definition video streaming, mobile distributed computing, wireless gaming, internet access, fast large file transfer and wireless personal area networks. The 60 GHz Band has several advantages such as the possibility for frequency reuse over small distances due to high oxygen attenuation of 10 to 15 dB/km, and the prospect for antenna miniaturization as the free space wavelength is 5 mm at 60 GHz. These advantages enable a 60 GHz system to be a suitable replacement for current short range wireless systems.[1-3]

System-on-Chip (SoC) is a promising solution for low cost wireless communication since it integrates the antenna, front and back-end circuits on one chip. Integration of the AoC with other circuits eliminates the costs associated with materials required for external antennas. Moreover, antenna matching circuits are eliminated as a 50 Ω boundary is no longer required. Finally, SoC enables a one step foundry fabrication of the entire wireless system. For further cost reduction, the cost effective CMOS process, a digital mainstream technology, is used to implement the AoC. Since the CMOS substrate is characterized by low resistivity and high permittivity; however, AoC performance is poor in terms of gain and radiation efficiency.[1-16]

Post processing design methodologies such as micro-machining[4] and proton im-



▲ **Fig. 1 Square AMC's two unit cells (a) HFSS setup (b) and reflection phase (c).**



▲ **Fig. 2 Circular AoC with AMC plane; top view (a) 3D view (b) simulated |S11| (c) and simulated peak gain and efficiency (d).**

TABLE 1

OPTIMIZED DIMENSIONS OF CIRCULAR AoC OVER SQUARE AMC

D	x_o	y_o	L_m	W_m	L_f	W_f	L_g	W_g
450	64	85	60	14	50	54	100	254

plantation[5] are used to improve AoC performance. Micromachining improves performance by selectively removing parts of the lossy CMOS substrate underneath the AoC.[4] Proton implantation enhances performance by implanting high energy ions in the area below the AoC, increasing CMOS substrate resistivity.[5] Even so, these two techniques increase the overall cost due to the additional processing. Electromagnetic shielding using Artificial Magnetic Conductor (AMC)[3,11-14] is another alternative. An AMC plane is composed of periodic metal patches in two or three dimensional configurations over a dielectric substrate. The AMC plane is characterized by a reflection coefficient of +1 at its center frequency, which enables wideband matching. In the AMC operating frequency band, high impedance is acquired due to the planar dimensions, leading to reduced surface wave propagation; hence, radiation efficiency of the AoC is enhanced. However, an AoC employing a symmetric AMC[11-14] suffers from a low gain to active area ratio. To enhance its gain to active area ratio, Barakat et al.,[3] introduced a method to increase the number of AMC cells in the direction of AoC polarization and limit the number of AMC cells in the perpendicular direction.

In this article, the use of an asymmetric rectangular (R-AMC)[15] is proposed in order to increase the gain to active area ratio without affecting other performance characteristics. Furthermore, an asymmetric R-AMC has a reduced insertion loss for extended feed lines when compared to a symmetric AMC. The design is optimized using the ANSYS High Frequency Structure Simulator (HFSS®) and the layout is done using Cadence Virtuoso®. Implementation is in 0.18 μm CMOS technology.

CIRCULAR AoC WITH SQUARE AMC

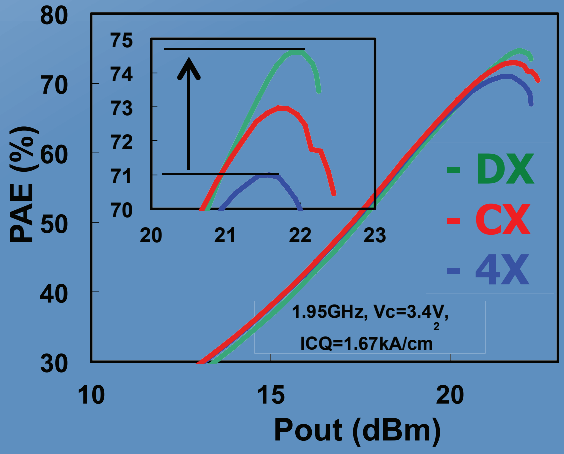
The reflection phase on an AMC plane varies with the frequency between ±180° and equals zero at its resonance frequency. The useful bandwidth of the AMC is generally defined in the range between ±90°.[3] The percentage AMC bandwidth (BW_{AMC}) can be expressed by

$$BW_{AMC} = \frac{f_{up} - f_{lo}}{f_c} \times 100\% \qquad (1)$$

where f_{up} and f_{lo} are the frequencies at which the reflection phase equals +90° and -90°, respectively. While, f_c is the center frequency at which reflection phase equals 0°.

A square AMC unit cell[3] is shown in ***Figure 1a*** and the simulation setup to optimize its reflection phase response is shown in ***Figure 1b***. Periodic boundary conditions (PBC) are realized using Perfect-E and -H boundaries. A wave port is used as an excitation port. The reflection coefficient (S_{11}) is embedded at the surface of the AMC unit cell and the reflection phase response is computed as the angle of the embedded S_{11}. The optimized dimensions of the square AMC are d = 260 μm and g = 30 μm with a bandwidth of 16.5 percent.

The square AMC is then used to enhance the performance of circular AoC following the approach described by Cohn.[16] According to this methodology, the gain to active area ratio of the AoC is enhanced by increasing the number of AMC cells in the direction of antenna polarization and decreasing them normal to this direction. The circular AoC with optimized AMC plane is shown in ***Figures 2a*** and ***2b*** and its optimized dimensions are listed in ***Table 1***. The simulated $|S_{11}|$ is shown in ***Figure 2c*** showing a bandwidth of 18 GHz. Its simulated gain and efficiency are -0.8 dBi and 22.5 percent, respectively, at 60 GHz as shown in ***Figure 2d***.


80
70
60
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30
PAE (%)
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Pout (dBm)
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21
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- CX
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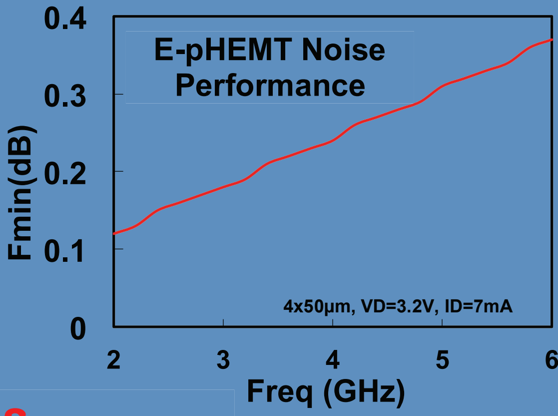
1.95GHz, Vc=3.4V,
ICQ=1.67kA/cm2


E-pHEMT Noise Performance
0.4
0.3
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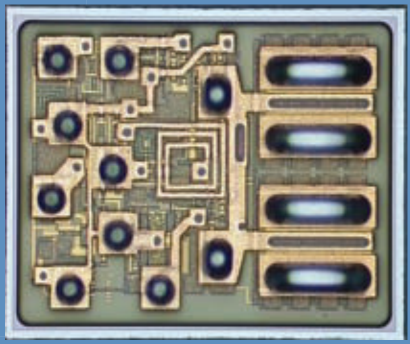


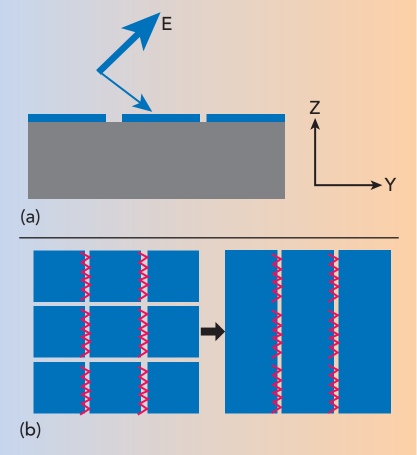
CIRCULAR AoC WITH ASYMMETRIC R-AMC

For a TM case, a wave with its E-field in the yz-plane and H-field in the x-direction as shown in ***Figure 3a*** is incident on a "Cohn square" in free space.[16] The observed E-field in the plane of the square AMC vanishes in the space between the edges parallel to the y-direction, thus reducing the square AMC to a strip array of asymmetric R-AMC as shown in ***Figure 3b***.[17]

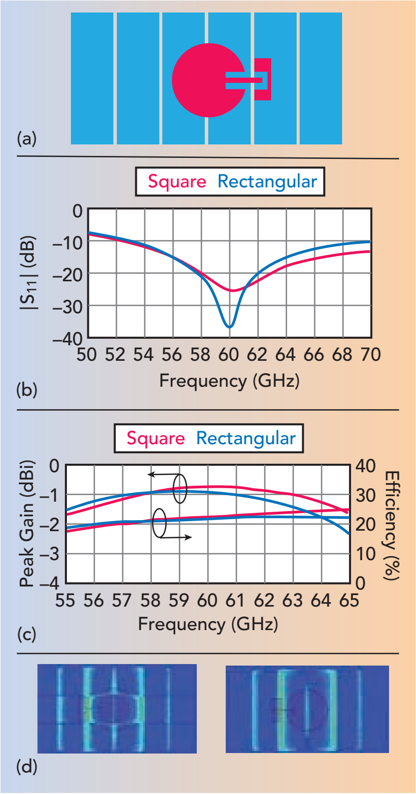
The asymmetric R-AMC is used to enhance the circular AoC as shown in ***Figure 4a*** and its dimensions are found in the same way as for a square AMC. The simulated $|S_{11}|$ of the circular AoC with asymmetric R-AMC and with square AMC are compared in ***Figure 4b***, showing no change in the resonant frequency and approximately the same matching performance. Gain and efficiency of the circular AoC with asymmetric R-AMC and with square AMC are compared in ***Figure 4c***. Approximately the same behavior is observed in both cases. Similarly, the electric field distribution in both cases is almost identical as can be interpreted from ***Figure 4d***. These observations show that square AMC and asymmetric R-AMC are equivalent for TM mode antennas.

CIRCULAR AoC WITH MODIFIED ASYMMETRIC R-AMC

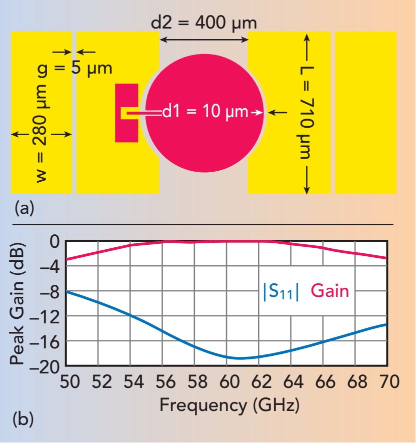
In order to further enhance the AoC gain to active area ratio, the asymmetric R-AMC plane is modified as shown in ***Figure 5*** by removing the two cells directly below the AoC. AMC cell removal for increased gain was initially proposed by X. Bao et al.[11] Additionally, the unit cell is limited in length (L) from 860 µm to 710 µm since in this direction the gain performance is negligibly affected. After that, the input matching of the AoC is improved by adding circular rounds to the AMC cells near to the AoC as shown in



▲ **Fig. 3 AMC in presence of incident TM wave; incident wave with E-field in yz-plane (a) original AMC and equivalent asymmetric AMC (b).**



▲ **Fig. 4 Circular AoC with asymmetric AMC plane; top view (a) simulated $|S_{11}|$ (b) simulated peak gain and radiation efficiency (c) current density with square AMC (left) and asymmetric R-AMC (right) (d).**



▲ **Fig. 5 Circular AoC over asymmetric R-AMC; top view (a) simulated $|S_{11}|$ and peak gain (b).**

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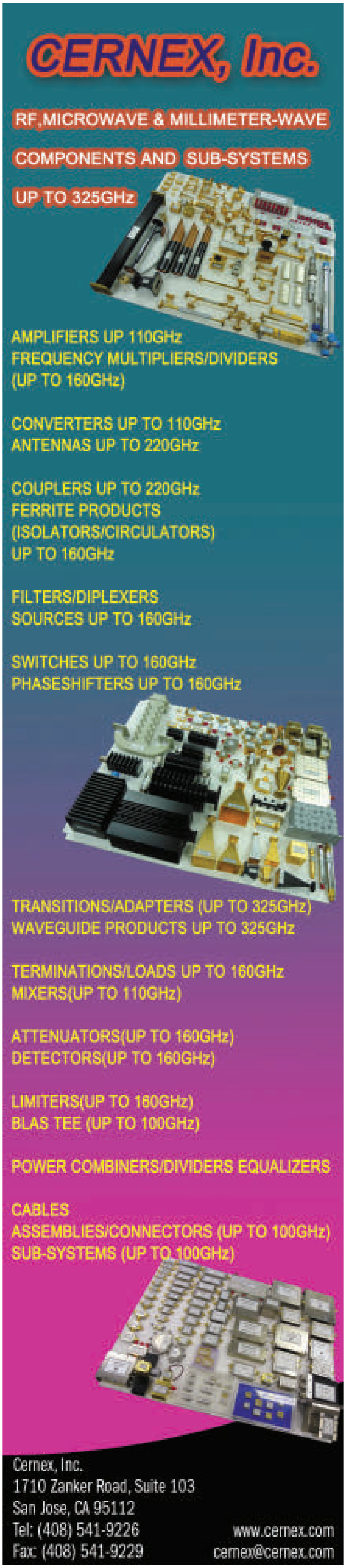
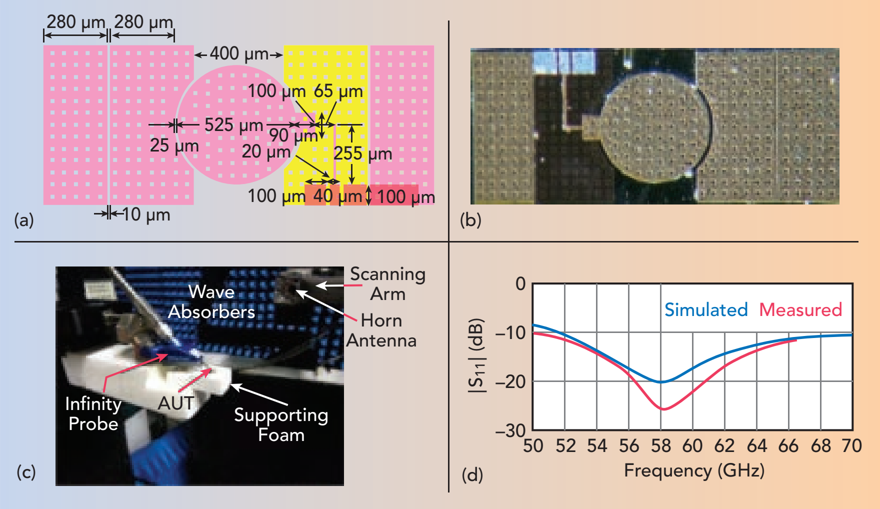




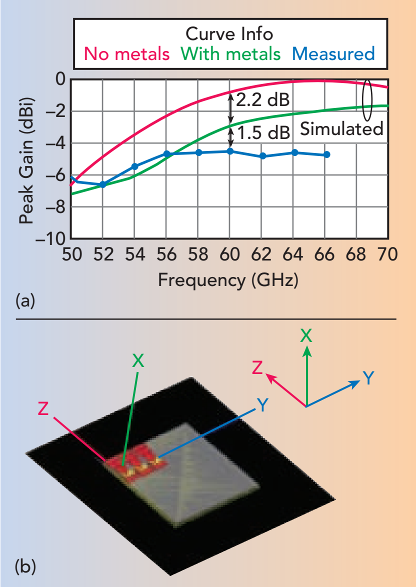
▲ **Fig. 6 Circular AoC over modified asymmetric R-AMC; layout (a) photo of fabricated chip (b) measurement setup (c) and simulated vs. measured $|S_{11}|$ (d).**

Figure 5a and then by optimizing the gap between the AoC and the modified AMC cells "d1" and the separation between the modified cells "d2". The simulated $|S_{11}|$ and peak gain responses of the antenna are shown in ***Figure 5b***. This antenna has a gain of 0 dBi at 60 GHz and its area is only 1.19 mm^2.

LAYOUT, FABRICATION AND MEASUREMENTS

The layout of the circular AoC with modified asymmetric R-AMC plane is shown in ***Figure 6a*** with a slight change in the feed position. The area is 1715 μm x 710 μm. The fabricated AoC chip photo is shown in ***Figure 6b*** with the measurement setup shown in ***Figure 6c***. The antenna is characterized using the measurement set-up described by Pan et al.,[19] using a 100 μm Infinity® probe. The calibration is done using a Cascade 101-190 calibration kit. The AoC is placed using supporting foam which is nearly invisible to the EM waves. A piece of metal is placed below the chip to account for the package ground. Measured and simulated $|S_{11}|$ of the fabricated AoC are compared in ***Figure 6d***. The measured results show good agreement with simulation.

Simulated and measured peak gain responses of the fabricated AoC are compared in ***Figure 7a***. Since the actual fabricated AoC is located on a chip corner, its simulated gain, noted as "no metals," is compared with measured results. Initially, a discrepancy of up to 4 dB is found between the measured and simulated results. Since simulated surrounding environment is metal free,[18] the discrepancy may be due to nearby metals, probe pins and the probe body which are not considered in simulations. In the simulation model shown in ***Figure 7b***, nearby metals expected to affect the measurements are considered. The probe's pins are modeled as suggested by Pan et al.[19] The simulated peak gain noted as "with metals" in Figure 7a is in better agreement with the measured results especially for frequencies up to 58 GHz. Further discrepancies between measured and simulated gain may be due to other metals which are not modeled, and also



▲ **Fig. 7 Measured gain vs. simulation (a) and HFSS model (b).**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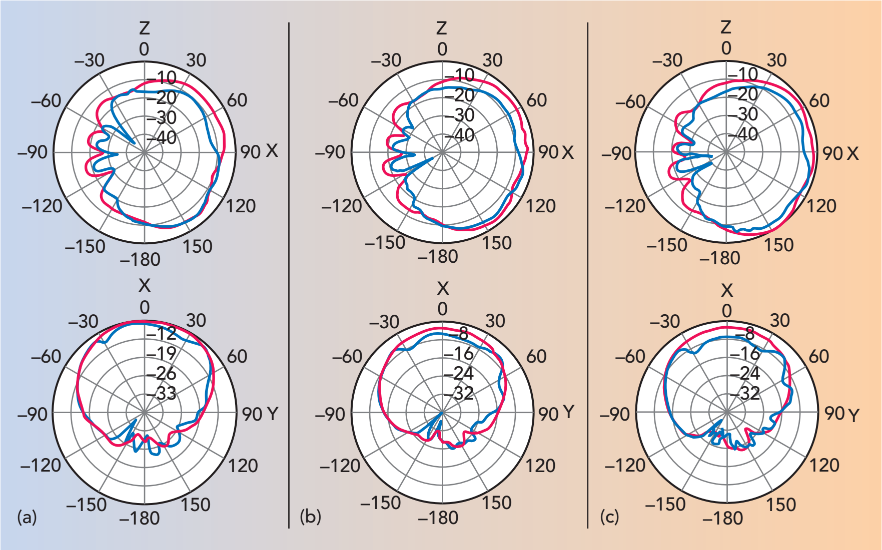

▲ **Fig. 8 E-plane (top) and H-plane (bottom) radiation patterns; 56 GHz (a) 60 GHz (b) and 64 GHz (c). Measured (blue), simulated (red).**

TABLE 2

PERFORMANCE COMPARISON

Reference	*This Work*	*11*	*13*	*14*
Process	0.18 µm CMOS	0.18 µm CMOS	0.18 µm CMOS	0.18 µm Bi-CMOS
Antenna Type	Circular Patch	Dual Loop	Patch	N/A
Measured Gain (dBi)	−4.3 at 60 GHz	−4.4 at 65 GHz	−0.5 at 60 GHz	−2.5 at 94 GHz
Area (mm^2)	1.22	3.24	10.89	2.6
Comments	Smallest Area	Circular Polarization	Off-Chip AMC	Meta-Surface as Radiator

due to the ± 0.8 dB accuracy of the measurement setup.[18]

Measured radiation patterns are shown in ***Figure 8***. The E-plane and H-plane are located at XZ and XY cut planes, respectively as can be interpreted from the coordinate system in Figure 7b. The patterns show some twist especially for the E-Plane.

A performance comparison is shown in ***Table 2***. Peak gain is the same or slightly lower than for other designs, while the fabricated antenna has the lowest chip area.

CONCLUSION

Asymmetric R-AMC is proposed for the purpose of enhancing gain and reducing the size of a circular AoC. The antenna design shows a peak simulated gain of -0.4 dBi at 60 GHz. The actual AoC, fabricated using 0.18 µm CMOS technology, demonstrates a peak measured gain of -4.3 dBi at 60 GHz with an overall area of 1.22 mm^2. Initial discrepancies in simulated versus measured gain are resolved by re-simulating the fabricated AoC considering probe pins and nearby metals expected to affect performance. Agreement between simulation and measurement is found for frequencies lower than 58 GHz. For higher frequencies, discrepancies on the order of 1.5 dB may be due to other nearby structures not considered in simulations. Measured and simulated radiation patterns are in good agreement.■

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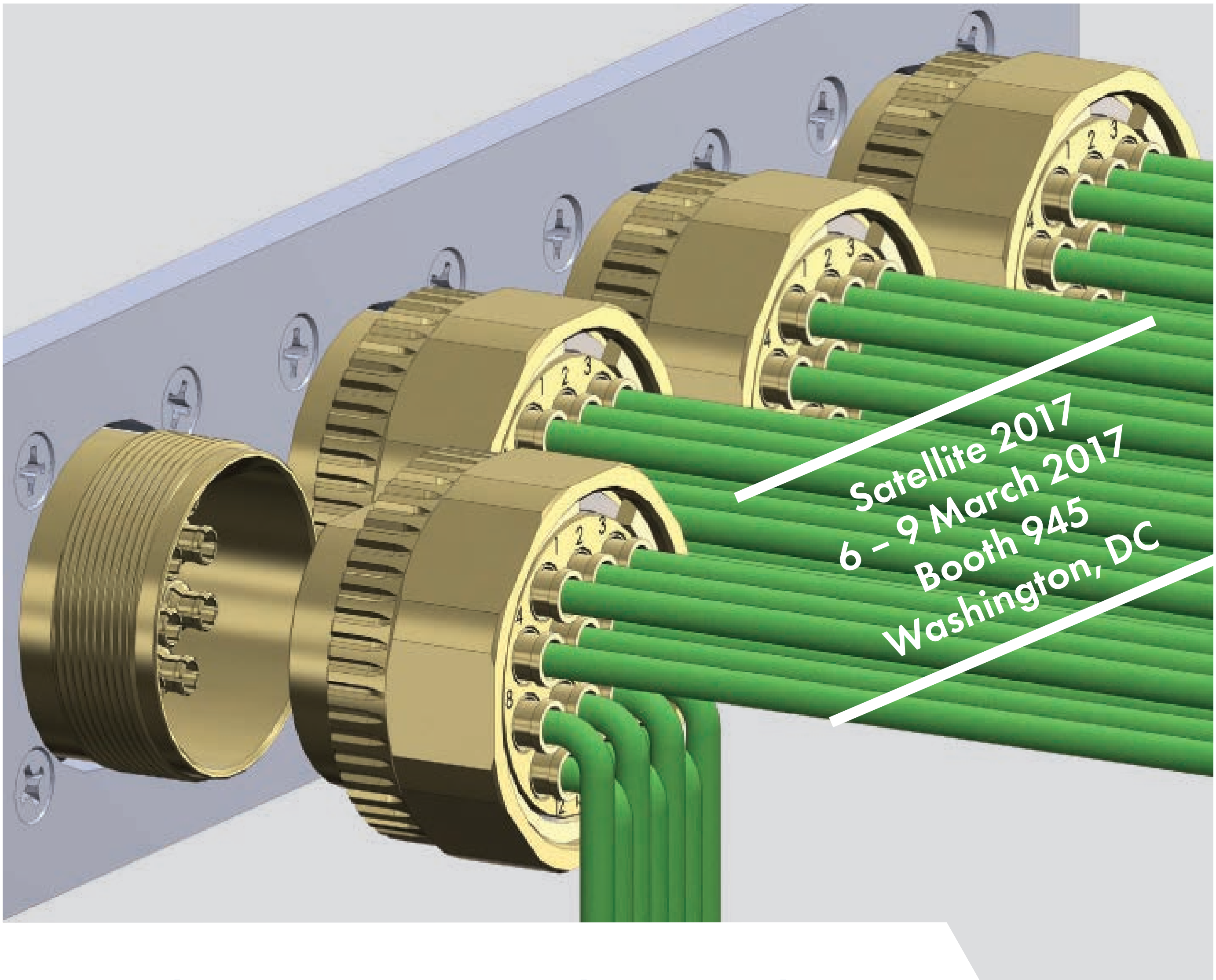
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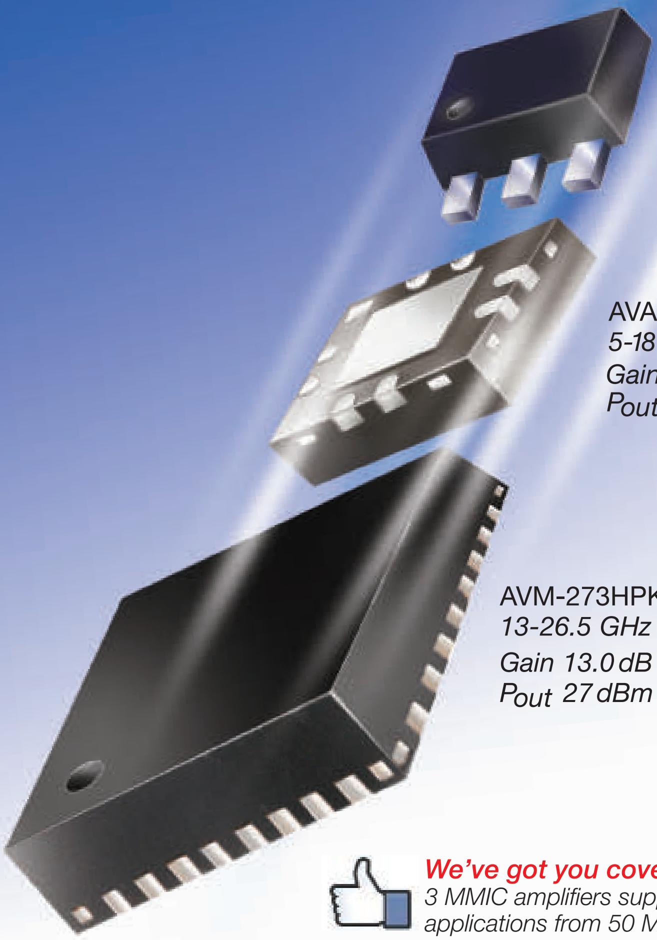

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Envelope Tracking in Handsets Solves a Network Problem

Joe Madden
Mobile Experts, Campbell, Calif.

LTE systems are uplink limited. While base station radios generally transmit at 60 W or higher for the downlink, a handset is currently limited to Power Class 3, which allows maximum transmitter power of +23 dBm ±2 dB at the antenna port. With similar propagation characteristics for downlink and uplink, the effective throughput for uplink LTE can be much lower than for the downlink. This is especially problematic at the higher frequency bands (e.g., 2.5 GHz), where the downlink can penetrate the wall of a building, but the uplink signal is about 6 dB weaker, and the two-way connection is lost. In LTE, the uplink is not optional, since the system needs a continuous uplink for channel estimation and power control. So uplink issues are simply perceived as poor coverage.

For TD-LTE, the time spent in uplink mode reduces the time available for downlink. This means that an inefficient uplink can reduce the capacity in the system for downlink traffic. The large TD-LTE operators, including Sprint and China Mobile, have pushed standards that support higher uplink transmitter power. Handsets with Power Class 2 operation should reach the market during the next year, with output power in Band 41 (i.e., 2.5 GHz) of +26 dBm ±2 dB. This is known as high power user equipment (HPUE) operation.

In today's mobile handset designs, targeting +26 dBm at the antenna port requires the power amplifier (PA) to have an output in the range of +30 to +32 dBm. Handsets with 15 or more bands have complex plumbing in the front end, with switches and filters between the PA and the antenna that contribute between 4 and 6 dB of loss. Adding HPUE operation requires the PA supporting the handset's high band transmitter to be redesigned. Doubling the output power typically results in a much larger amplifier; however, during most operating conditions the efficiency will be lower than before, and more heat will be dissipated. It's a waste of battery power to simply scale up the PA. Traditional amplifier designs have adopted average power tracking (APT), where the power supply is set to a static voltage based on the average RF power level. In many cases, sections of the PA can be switched in or out of the circuit, allowing the use of a smaller amplifier at lower power levels to improve efficiency. APT typically improves efficiency compared to a simple PA.

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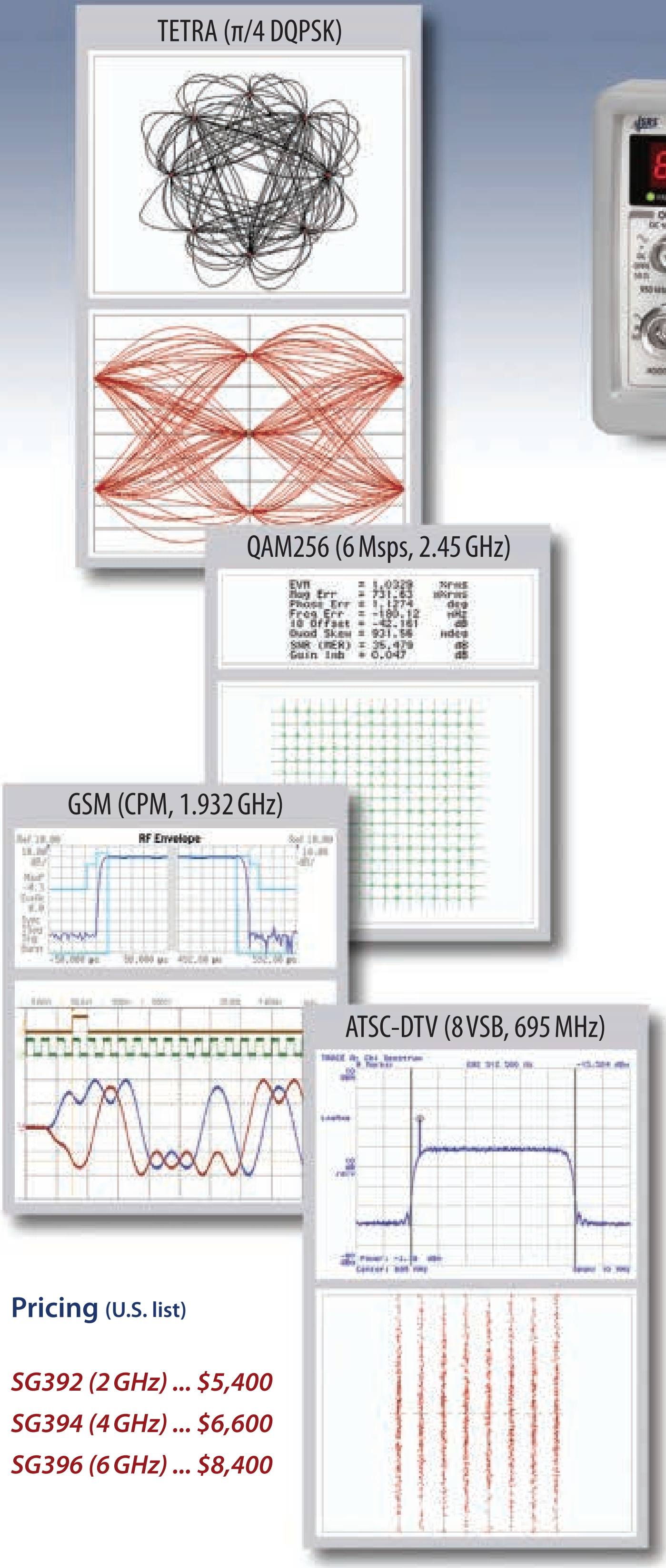

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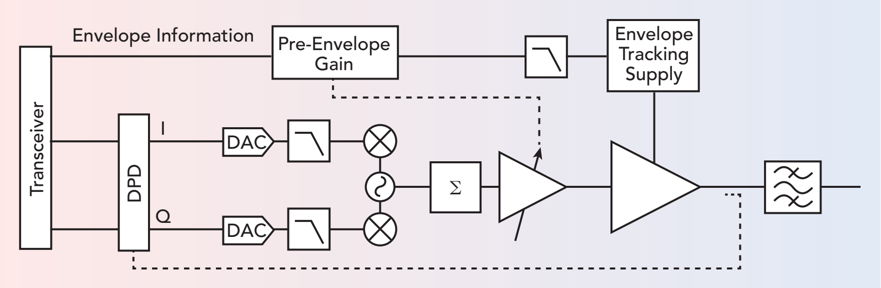


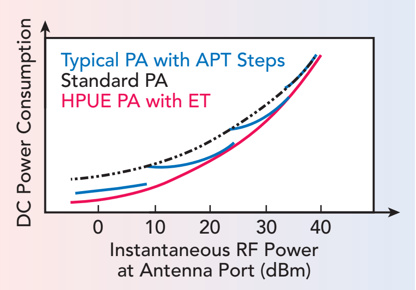
▲ **Fig. 1** **Simplified block diagram of ET in a handset transmitter.**

supply voltage to the amplifier (see ***Figure 1***). As the waveform ramps up for high peaks in the signal, the power supply provides the PA with higher supply voltage. In future HPUE implementations, the power supply will boost the supply voltage higher than the 3.5 V battery voltage in the handset. As the bias voltage changes, the operating point of the PA tracks to operate at its highest efficiency. When implemented properly, this approach results in the best possible efficiency at every operating point, with longer battery life and less heat dissipation in the handset. ***Figure 2*** compares the efficiency of the three PA architectures.

ET DESIGN CHALLENGES

Digital predistortion (DPD) is an important part of making ET work. As ET technology has developed over the past 20 years, designers have found that semiconductors exhibit "memory effects," where the device's distortion depends on the RF power during the previous 10 to 20 ns. Essentially, the instantaneous temperature in the device channel impacts the distortion. To compensate, DPD takes recent power levels into account, applying a tailored cancellation signal to offset intermodulation distortion. DPD can improve efficiency by allowing the designer to choose a smaller PA and run it further into compression during signal peaks, because the DPD compensates.

ET generates out-of-band noise, due to the imperfect performance of the wideband modulator applied to the power supply. Close integration of the ET PA with a filter is important to eliminate these spurious emissions without losing efficiency. While Figure 1 shows the filter as a separate component, it's important to co-design the filter with the PA. Matching each component to 50 Ω would greatly reduce efficiency.



▲ **Fig. 2** **Instantaneous efficiency of three PA architectures.**

The ET approach requires tight coordination between the modem chipset, power supply IC and amplifier. These three components must be carefully aligned to control the gain and time delay between the power supply voltage and the RF waveform. Precise calibration of the delay in production is critical to producing hundreds of millions of handsets. Achieving such tight control requires give-and-take between the transceiver, PA and power supply vendors. For this reason, the leading ET solutions come from chipset companies that supply all three functions.

Boosting a small amplifier to higher output power avoids scaling to a larger, less efficient PA. An ET system boosts the power supply to higher bias voltages—higher than the nominal 3.5 V of a handset battery using the right power supply components—which increases the operating point of the PA beyond its previous limits without sacrificing efficiency. APT amplifiers can also boost the power by supporting higher bias voltages. However, an APT implementation is less efficient for high power LTE, because the constant fluctuation of power in a high peak-to-average waveform results in significant time spent under

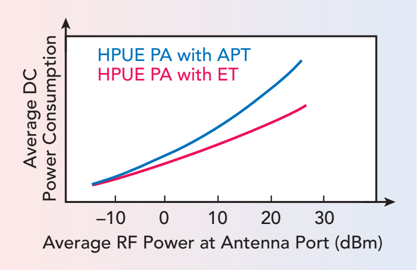


Fig. 3 APT vs. ET PA efficiency with a high PAR waveform.

inefficient operating conditions (see ***Figure 3***). Also, ET will be easier for many OEMs to accept than APT: with an ET solution, the modified power supply is provided by the same vendor as the transceiver. In the APT case, an additional power supply device must be added to the handset, taking up board space and adding cost.

MANUFACTURING CHALLENGES

ET manufacturing has proven to be as challenging as the basic technology. Introducing ET to high volume handset production during the past two years revealed problems calibrating the time delay and gain settings. One requirement is calibrating the delay in the RF path and the timing of the power supply envelope. In the early development of ET, with signal bandwidth of 1.25 MHz, delay was not critical; more than 10 ns was acceptable. With a 20 MHz LTE signal, the delay mismatch over all operating conditions must be below about 2 ns. Next year, when 40 MHz LTE channels implement ET, delay mismatch must be less than 1 ns. Production testing has evolved to tackle this challenge, with additional hooks built into the transceiver so the transceiver receives feedback on the delay mismatch and can automatically minimize it.

Gain over temperature has also been a production headache. A handset OEM typically characterizes about 10 handset models over 10 to 15 frequency bands and some 10 temperatures. The OEM then creates a lookup table to adjust PA gain over temperature. This tedious task can cost at least $100,000 for test chambers, equipment and technician support. For an OEM that makes 200 million handsets, this cost—$0.0005 per handset—is trivial. However, for an OEM that manufactures only one million handsets of each design, the cost is $0.10 per handset. To address this, DPD introduces a feedback path to sense the output signal, and this information can be used to reduce the cost and hassle of testing. When implemented, characterization testing can be reduced to just a single test at room temperature.

Fig. 4 Galaxy S7 smartphone.

The benefits of ET have been realized in most recent premium handset models, including the Samsung Galaxy S7 (see ***Figure 4***), the Xiaomi Mi5 and many others. Calibration and characterization are still expensive in these production models, but it's clear that high volume experience will lead to cost savings and process simplification over time. New ET devices in flagship smartphone platforms are already making significant strides to streamline manufacturing.

CONCLUSION

As video chat and augmented reality (AR) applications rise in popularity, uplink data capacity will become more important. Today, Band 41 operators are pushing for HPUE operation; in a few years, higher power operation will be required in all TDD bands, as well as high frequency FDD bands without legacy 2G/3G/4G technology, such as Band 7 (i.e., 2.5 GHz uplink). No smartphone OEM wants to add another power supply to boost voltage, and nobody wants to waste battery power. ET should become commonplace in mid-tier handsets as well as premium platforms over the next two years.■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Antenna Design Methodology for Smartwatch Applications

Phil Lindsey
ARSI LLC, Atlanta, Kan.
C. J. Reddy
Altair Engineering Inc., Hampton, Va.

In the early 1990s, Mark Weiser of Xerox predicted that computers would find their way into every part of our daily lives by integrating seamlessly and unobtrusively—a concept he termed ubiquitous computing. "The best user interface," Weiser observed, "is the self-effacing one, the one that you don't even notice." He predicted the advent of a wireless network of connected devices, making information accessible at any time and in any place. According to Weiser,[1] "In the long run, the personal computer and the workstation will become practically obsolete because computing access will be everywhere: in the walls, on your wrist and in 'scrap computers' (like scrap paper) lying about to be used as needed."

The technological world transforms daily into the likeness of Weiser's vision. Smart devices, particularly those that are wearable, like smartwatches, have touched and enhanced all aspects of our lives, from the way we conduct business to the way we relax at the end of the day. The particular advantage of wearable technology comes to the forefront in health and fitness. Wearable devices can monitor heart rate, skin temperature, distance traveled, even food intake and sleep patterns. Currently, most fitness trackers are mounted on wristbands like watches; a few even include watch functions.[2]

The pocket watch was invented in 1762.[3] Although this was a significant revolution, placing the ability to keep time at the fingertips of the common person, instead of the elite, had its disadvantages. If the hands of the user were already full, the manipulation of a pocket watch was just too much hassle—thus, the invention of the wristwatch and its widespread acceptance among British soldiers during World War I.[4] The wristwatch quickly became among the most common wearable devices in the world, making it a prime candidate for enhancement with computer power. Calculator watches first appeared in 1975. They were followed by a wrist PC in the 1980s and a watch with a built-in arcade game.[3] Later smartwatches have only increased their capabilities. 2000 saw what is believed to be the first collaboration between a clothing company and a digital technology company, when Nike and Apple joined to create a fitness tracker embedded in a shoe and designed to work with an iPod. This Nike+ tool was developed to help runners track time, distance, pace and calories burned. Eight years later came the Fitbit Classic. Fitness trackers have flourished, more or less, since.[3] According to mobile communications analysts, the wearables market could be worth $34.2 billion by 2020. Shipments of fitness trackers are expected to reach over 60 million units in the next year or so, while smartwatches are forecast to exceed 30 million units.[3] Computing access is indeed everywhere.

CHIP ANTENNAS

Ubiquitous computing makes good antenna design essential. Smart device antennas must be small and flexible to fit in small, predefined environments. Some research suggests that the bulkiness of smartwatches has tempered their popularity.[5] To be useful, these devices need to operate reliably for a long time without the user needing to modify his or her activity to accommodate the device. This means that the antenna must respond to movement and be immune


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to the near field effects of the human body. The battery life of the device must also be sufficiently long to satisfy the user. This is largely a function of good antenna design, as most of the energy a smart device uses is consumed during RF transmission. Finally, the completed device must meet user expectations for price and the FCC's requirements for safety.[6]

One solution to these design challenges is the chip antenna. A chip antenna is small and efficient enough to be integrated neatly into a compact smart device, and it is easy to tune.[7] Compared to other options, chip antennas are relatively inexpensive, yet effective. These chips are typically based on helix, meander or patch antenna designs.[8] Because of their cost effectiveness, small size and mechanical viability, analysts forecast the global market for the chip antenna to grow at a 10 percent compound annual growth rate (CAGR) from 2016 to 2020. As more devices trend to wireless connectivity, the boom in smart devices is spurring competition between the various chip vendors, including Vishay Intertechnology, Antenova Ltd., Johanson Technology, Mitsubishi Materials and Fractus.[9]

As with all product developments, designing with chip antennas presents challenges that must be accounted for in the initial circuit design. Recall that we are dealing with small devices. This presents a difficulty because the smaller the antenna, the harder it is to achieve good impedance matching and a large bandwidth.[10] Therefore, performance is highly dependent on the placement and size of the antenna.[7] Second, datasheets reflect the chip on a board, and any variation in the ground plane will change the antenna pattern and impedance. The overall performance of any chip antenna is always dependent on the whole system; it must be compatible with the size and layout of the board, the complexity of the circuit and the type of enclosure.[8] Also, it must not negatively affect any sensors in the device.[7] Finally, on a person, the highly variable dielectric constant of different body tissues causes the blockage and impedance to change.[11] Human tissue is extremely lossy, so electromagnetic energy from an antenna on the body will not propagate through the body and radiate into space as intended, but will largely be absorbed.[10] The results are bulk power absorption, radiation pattern distortion and antenna detuning.[11] Losses can block coverage to other devices or reduce the range of the antenna.

To address these design challenges, a systematic design approach has been developed:

- Choose a chip antenna with a demo board
- Model the chip antenna without the board
- Model the chip antenna with the board
- Measure the chip antenna on the board
- Validate the model with the measured data
- Model the chip antenna in the smart device
- Model the device with a human phantom.

This methodology provides a valid starting point that eliminates a plurality of unknowns. By following the procedure, installation concerns can be addressed with confidence.

For this article, we used a commercially available electromagnetic simulation tool, FEKO[12] and its various full wave solvers, to model the antenna, including the packaging and enclosure of the smart device. The finite element method (FEM) solver is a perfect tool for complex multi-dielectric volumes in close proximity to an antenna. By using the FEM solver, the ground plane can be modified to fit the smart device package and verified to operate properly. Extending the simulation to include a phantom model will show power absorption, radiation pattern distortion and antenna detuning problems that need to be addressed. Given the computational complexity of adding an entire phantom, we used the source decomposition method in FEKO to represent the FEM region of a device as a near field source, then applied the decomposed source to the full phantom model using either the method of moments (MOM) or multi-level fast multipole method (MLFMM).

CHIP ANTENNA MODELING

For the smartwatch design, we chose a Fractus Slim Reach Xtend chip antenna (FR05-S1-N-0-104). This chip has been engineered for wireless applications operating in the 2.4 GHz Bluetooth band. The Slim Reach Xtend has the advantages of being small, cost effective and relatively easy to design with, avoiding the need to test multiple antennas with different resonant frequencies.[13] The Slim Reach Xtend datasheet shows the configuration used to determine the performance in the specifications. By integrating the chip antenna with the evaluation board, which can be purchased (EB_FR05-S1-N-0-104), the measured performance can be compared to the modeled simulation, providing a verified model to be used in any smart device design.

From a close-up of the Fractus chip, the traces on the chip and the geometry of the evaluation board were scaled using a caliper and entered into the FEKO 3D Modeler, CADFEKO. With this information, an FEM model of the Fractus chip on the evaluation board was created. ***Figure 1*** shows a photo of the Fractus chip and the FEM 3D model. The model was run with FEM Solver in FEKO to compute the currents, impedance and antenna patterns. ***Figure 2*** shows the 3D radiation pattern around the chip on the evaluation board. The evaluation board acts like a dipole antenna whose arms lie along the y-axis, accounting for the resulting nulls along that axis.

A comparison of the measured and modeled $|S_{11}|$ of the evaluation board (see ***Figure 3***) shows good agreement for the 10 dB bandwidth, well within acceptable parameters, and the tuned frequency results were nearly identical. This shows excellent correlation between the model and the real board, validating the models of the chip and the chip on the board. This was the first attempt in the modeling and validation process; no other validation steps were required.

SMARTWATCH INTEGRATION

The chip antenna and feed network were integrated into a smartwatch (see ***Figure 4***). As the already

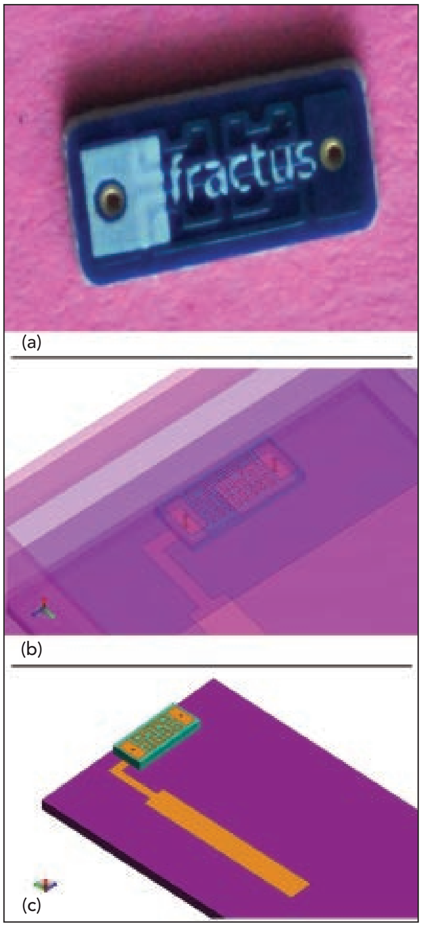


Fig. 1 Fractus chip antenna photo (a) and FEM model of the chip (b) and evaluation board (c). Courtesy: VStar Systems Inc.[14]

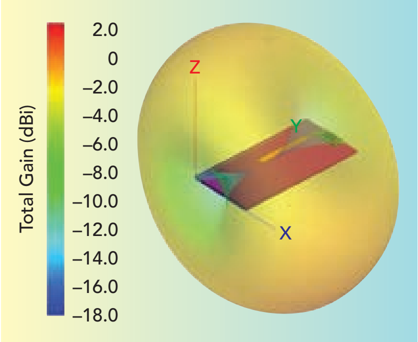


Fig. 2 Simulated 3D radiation pattern around the Fractus chip antenna evaluation board. Courtesy: VStar Systems Inc.

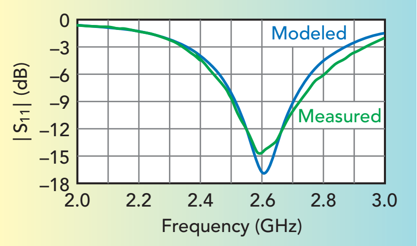


Fig. 3 Measured and simulated $|S_{11}|$ of the Fractus chip antenna evaluation board.

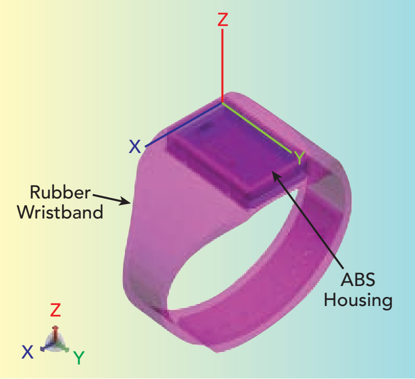


Fig. 4 Smartwatch showing the chip and feed network.

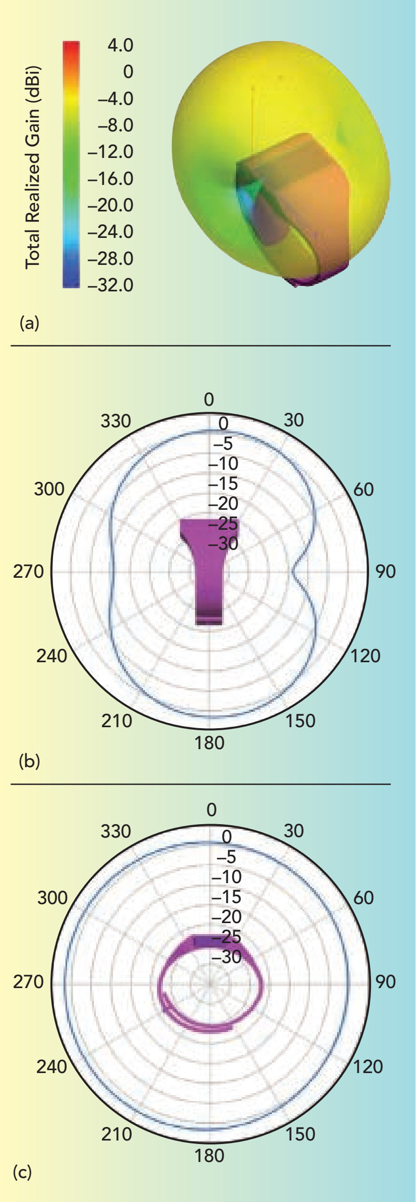


Fig. 5 Smartwatch simulated 3D antenna pattern (a) and far field antenna gain for $\varphi = 90^\circ$ (b) and $\varphi = 0^\circ$ (c) at 2.45 GHz.

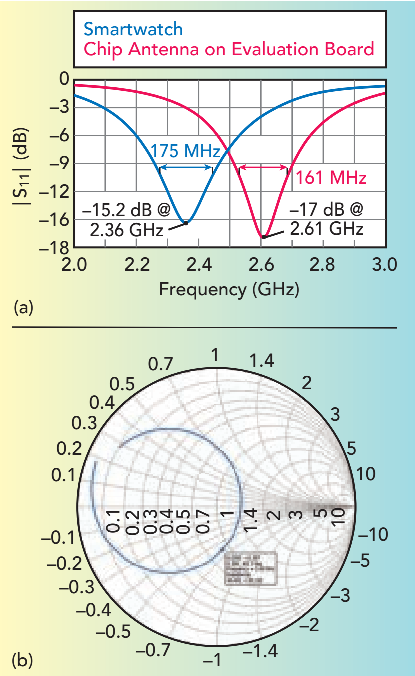
complex dielectric geometry of the chip and evaluation board became more complex with the addition of the rubber wristband and ABS plastic electronics housing, the FEKO FEM solver was again selected for simulation. The completed FEM model of the smartwatch geometry was modeled with the solver, calculating the input port impedance, currents and the 3D radiation patterns. ***Figure 5a*** shows the simulated 3D antenna pattern of the chip and PC board embedded in the ABS enclosure and wristband inside the watch. The resulting nulls along the y-axis of the watch maintain the dipole-like pattern along the long axis of the board. The nulls are in the desired position: wearing the watch with the arms down, the nulls in the radiation pattern are directly down to the ground and directly up (the nadir and zenith). Most of the power should be going around the wearer of the watch, and that is what the results show will happen. ***Figure 5b*** shows a $\varphi = 90^\circ$ cut of the radiation pattern, with the up and down nulls at $\theta = 90^\circ$ and $\theta = 180^\circ$. The radiation pattern around the arm is omnidirectional, as shown in ***Figure 5c***.

Integrating the chip antenna into the watch changes the impedance (see ***Figure 6a***). The base model has a resonance of 2.6 GHz and a bandwidth of 161 MHz. Embedding the antenna into the surrounding dielectric material reduces the resonant frequency because the dielectric constant of the containing volume is higher. The minimum $|S_{11}|$ drops in frequency since the antenna appears larger. The resonance frequency was reduced from 2.6 to 2.35 GHz, and the bandwidth was increased from 161 to 175 MHz. Note that the resonance frequency drops below the desired Bluetooth band (2.4 to 2.5 GHz). This must be addressed in the final design by adding a matching network to move the response into the Bluetooth band and will not be difficult (see ***Figure 6b***). It is always good practice to place a pi network between the antenna and the transceiver. In this case, a shunt inductance along with a series inductance will tune the antenna to the center of the Bluetooth band while maintaining the bandwidth.

HUMAN PHANTOM MODEL

The final step in the design process is to integrate the smartwatch into a full human phantom model to investigate the radiation patterns of the smartwatch in proximity to the human body. Because of the size of the problem, the resources required to run the finite element model of the watch and the human phantom together were prohibitive. Therefore, source decomposition was used to break the problem into two sections: an equivalent source representation of the watch and the equivalent source integrated into the phantom model. Near fields were run around the FEM model of the watch to create an equivalent source to use with the phantom model. Then the MLFMM solver in FEKO was used to solve the phantom. This process greatly reduced the resource and time requirements without compromising accuracy.

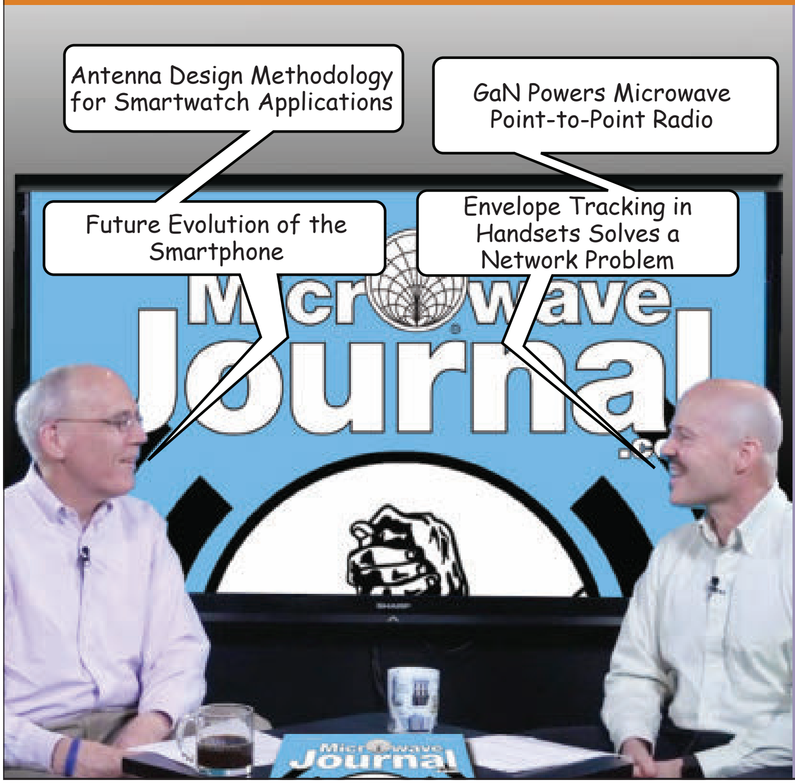
Figures 7a and *b* show the 3D antenna radiation around the phantom. As expected, the human body is blocking the radiation patterns to the left-hand side, the side opposite the smartwatch. Since the arm is not stationary during normal activity, a connection will normally be maintained between the smartwatch and other transceivers. Excellent radiation patterns are obtained in the front, back and right-hand side of the human body model. ***Figure 7c*** shows the antenna radiation on the horizon around the phantom. The peak gain is just less than 5 dBi, and the overall coverage will meet the requirements for a typical single transceiver design.

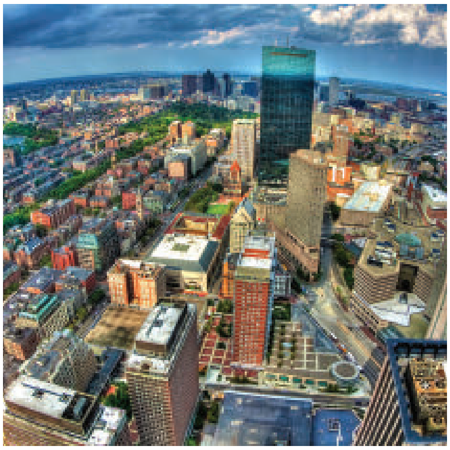


▲ **Fig. 6 The smartwatch structure "tunes" the antenna, reflected by a change in $|S_{11}|$ (a) and impedance vs. frequency (b).**

CONCLUSION

Designing antennas for wearable smart devices presents a unique set of challenges, i.e., dealing with small environments and lossy human tissue. While the chip antenna offers the efficiency necessary to offset some of these problems, concerns must be addressed during the initial circuit design. Placement, compatibility with the whole system and reliability on a human must be taken into account. To address these, it is beneficial to establish a valid model of the chip antenna that can be integrated into other devices with





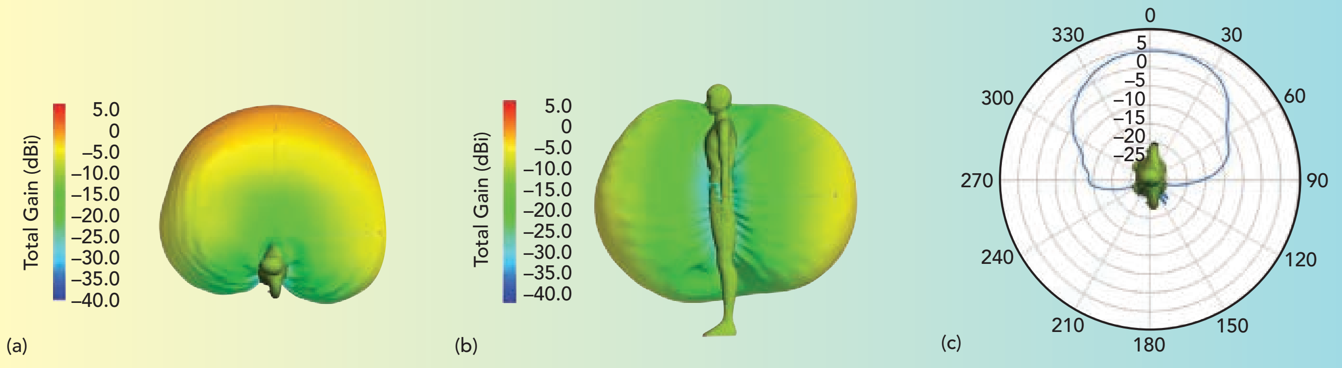


Fig. 7 Simulated 3D antenna pattern using the full human phantom model, with the smartwatch on the right wrist. Top (a) and side (b) views and far field antenna gain with Θ = 90° (c) at 2.45 GHz.

a high level of confidence. As this article demonstrates, using multiple FEKO solution techniques can solve complex geometric problems with high accuracy. This results in a valid model that can be used to design future applications with high confidence in achieving satisfactory real world results. ■

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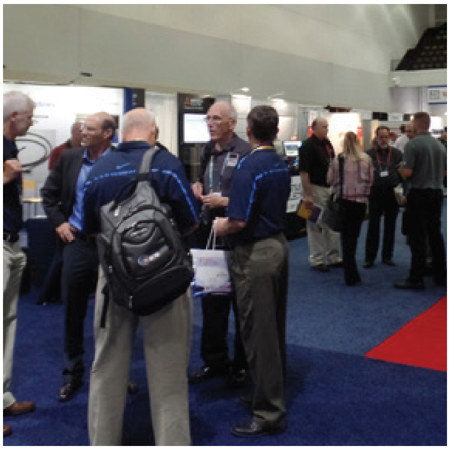

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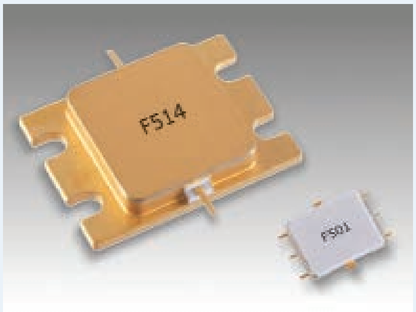

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The F501 is a compact, surface-mount, hybrid module that can be used as the power amplifier (PA) in a phased array radar or as the driver for a higher power PA. The two-stage, internally matched amplifier has typical performance of greater than 30 W saturated output power (45 dBm) with 38 percent power-added efficiency and 23 dB gain across 8.5 to 10.1 GHz. The hybrid PA is also assembled in a hermetically-sealed package.

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Low Noise, Low Cost, "Plug n' Play" YIG-Based Synthesizer

Teledyne Microwave Solutions (TMS) has developed a family of YIG-based synthesizers that reduces the traditional high cost of a high quality, low phase noise, broadband frequency source. These modular YIG designs simply plug into a laptop or desktop using the USB connection to create a fully functional synthesizer, one that has superior performance to the industry standard architecture based on voltage-controlled oscillators (VCO).

Various models are available, operating in bands from 2 to 13 GHz. One design spans 6 to 13 GHz with 1 MHz step size. The output frequency is set with a simple "set frequency" command from the PC. At 6 GHz, the phase noise is -70 dBc/Hz at 100 Hz offset, -90 dBc/Hz at 1 kHz, -95 dBc/Hz at 10 kHz, -125 dBc/Hz at 100 kHz and -145 dBc/Hz at 1 MHz offset. Spurious signals are a maximum of -60 dBc, and harmonics are no greater than -20 dBc. The nominal output power is between +10 and +16 dBm. A 10 MHz frequency reference signal is required, nominally around +5 dBm. The synthesizer is powered with +12 V DC and draws a maximum of 600 mA. The operating temperature range is +10° to +50°C.

TMS synthesizers can be configured in a variety of shapes, sizes and frequencies to meet custom requirements. Serial interfaces are available, in addition to USB. By offering low phase noise YIG oscillator technology in a complete synthesizer, TMS offers a high performance integrated solution with a better ROI than other industry options.

Teledyne Microwave Solutions
Mountain View, Calif.
www.teledynemicrowave.com

18 to 40 GHz Transceiver

Spacek Labs has developed an 18 to 40 GHz transceiver, the TRRKKa-9HVA, comprising one transmit and two receive channels. Each of the two down-converting receive channels comprise a 70 dB programmable attenuator, low noise amplifier (LNA), switch for selecting 18 to 26.5 GHz or 26.5 to 40 GHz, an RF lowpass filter (for image and LO rejection) and mixer. The programmable attenuators have 2 dB minimum insertion loss, and the LNAs have 4.5 dB noise figure with 20 dB gain, typical. The mixers in the down-converters use a balanced crossbar design and achieve a conversion loss of approximately 7 dB.

The transmit channel contains an up-converting mixer, RF lowpass filter, power amplifier, band switch, polarity switch (vertical and horizontal) and an antenna switch at the output. The up-converting mixer is also a balanced crossbar design with 7 dB conversion loss. The lowpass filter following the mixer rejects the LO and image frequencies, the image by more than 50 dB. The output amplifier has approximately 45 dB gain with an output power at 1 dB compression of greater than +28 dBm, typical, from 18 to 40 GHz.

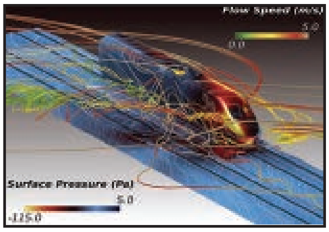
The LO chain comprises a fundamental phase-locked oscillator (PLO) with a 10 MHz external reference. The PLO is switched between the x3 and x4 active multipliers, both with output bandpass filters. The x3 output drives the three K-Band mixers, and the x4 output drives the three Ka-Band mixers. Filtering keeps the upper and lower sidebands of the RF signal from entering the LO chain yielding a channel isolation of greater than 60 dB.

Spacek Labs
Santa Barbara, Calif.
www.spaceklabs.com


© Neal Miyake

Software and Mobile Apps

HyperWorks® 14.0



Altair's HyperWorks® 14.0 open architecture CAE simulation platform includes several new products, feature enhancements, updated functionalities and licensing methods to help users. Key highlights: expanded optimization and nonlinear solver capabilities; accelerated meshing, assembly and graphics; plus new tools and products in the Altair Partner Alliance. This release also introduces parts and assemblies in HyperMesh that directly correspond to those in the CAD and PDM world.

Altair Engineering Inc.
www.altair.com

App of Knowledge

VENDORVIEW

AR RF/Microwave's mobile app is available as a free download from Apple iTunes and Google Play. This application is a quick and easy tool to access a variety of content from AR. The home screen icons allow easy navigation to view basic and full product descriptions, app notes, AR's literature library, YouTube videos, contact information, social media activity and more—all from your mobile device. To download the app, visit www.arww-rfmicro.com/html/ar-moblie-app.asp.

AR RF/Microwave Instrumentation
www.arworld.us

RF Tools App

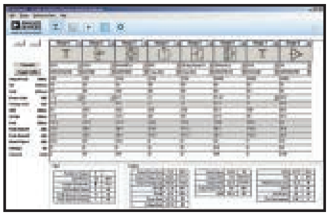
VENDORVIEW

The RF Tools app from HUBER+SUHNER is a free tool that can be downloaded in English and Chinese on Apple's app store now. RF Tools shows the relation between RF specific values such as impedance, wavelength, return loss (VSWR) and signal delay—including their conversion. It includes products such as connectors, cables, cable assemblies, antennas, lightning protectors and passive components, and finds your nearest branch and contact person.

HUBER+SUHNER AG
www.hubersuhner.com

ADIsimRF 2.0

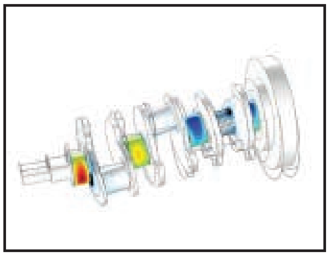
VENDORVIEW



ADI released the newest version of ADIsimRF, its popular RF signal chain simulator. ADIsimRF 2.0 significantly expands the tools capabilities. Signal chains with up to 50 stages can now be simulated. Frequency, power and gain sweeps are supported and results can be plotted and exported to excel. The component library has been expanded to approximately 500 devices and support has been added for RF DACs and wideband transceivers. Device selection is now easier with the addition of a device selection wizard. Download today at www.analog.com/adisimrf.

Analog Devices Inc.
www.analog.com

Rotordynamics Module



The latest update of the COMSOL® software product suite includes the new Rotordynamics Module, which will aid engineers in analyzing vibrations due to centrifugal forces and other gyroscopic effects in rotating machinery. This new product will be used to ensure that rotor vibrations are contained within acceptable design limits by providing functionality for evaluating critical speed, whirl and bearings. This module will be of particular interest to those working with the design of turbines, turbochargers, electrical machinery and pumps in the automobile, marine, aerospace, energy and household appliance industries.

COMSOL Inc.
www.comsol.com

Filter Wizard

K&L Microwave's Filter Wizard® synthesis and selection tool streamlines identification of RF and microwave filters meeting customer requirements across a large portion of K&L's standard product offerings. Filter Wizard® accelerates user progress from specification to RFQ over an ever-increasing range of response types, bandwidths and unloaded Q values. Provide the application with desired specifications, and the software returns a list of products that match, placing response graphs, outline drawings and downloadable s-parameters at your fingertips. Visit www.klfilterwizard.com via computer or mobile device to get started.

K&L Microwave
www.klfilterwizard.com

Software and Mobile Apps

Data Analytics

VENDORVIEW

Keysight's N8844A Data Analytics Web Service Software addresses designers' needs to analyze their test results more quickly and intuitively. It enables them to gain insight into reference designs, understanding design constraints and their impact on system margins. The new software provides the latest data on a histogram, can create custom graphs, data filtering/graphing and more. In combination with the visualization capabilities, the software enables users to make faster design decisions and reduces time to market.

Keysight Technologies Inc.

www.keysight.com/find/data-analytics

NI AWR Design Environment V13

VENDORVIEW

Next-generation communication and aerospace systems call for complex wireless devices and infrastructure that will challenge engineers to design smaller, faster and smarter products. NI AWR Design Environment V13 advances the state of simulation and design automation for RF/microwave and wireless communication electronics with new models, enhanced speed and functionality, and design flow integration. This open design platform provides system, circuit, and electromagnetic co-simulation to ensure first-pass success. Experience NI AWR Design Environment V13 with your free trial at awr.com/try.

National Instruments

awr.com/try

Sonnet Suites Version 16.54

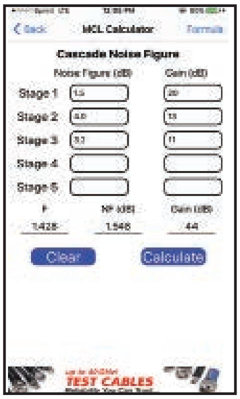
Sonnet® Software introduced Sonnet Suites Version 16.54 which supports an improved partner flow with NI AWR Version 13, known as AWR Connected™ for Sonnet. Sonnet's improved Microwave Office interface boasts 64-bit compatibility, asynchronous EM simulations, and is perfect for PCB and MMIC design applications. The improved flow provides an integrated "solver on request" interface that gives users the capability to stay entirely within the MWO environment while taking advantage of Sonnet's high accuracy simulation engine, ***em®***. Contact Sonnet to upgrade today.

Sonnet Software Inc.

www.sonnetsoftware.com

Microwave Calculator

VENDORVIEW



MCL Calculator

Cascade Noise Figure

	Noise Figure (dB)	Gain (dB)
Stage 1	1.5	20
Stage 2	4.0	13
Stage 3	3.2	11
Stage 4		
Stage 5		

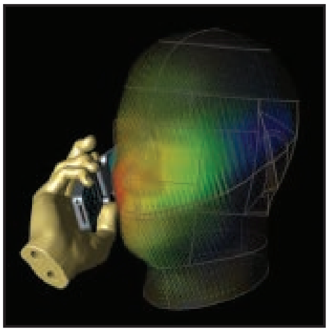
F	NF (dB)	Gain (dB)
1.428	1.548	44

Mini-Circuits' Microwave Calculator performs 21 calculations commonly needed by RF/microwave system designers in a wide range of applications. Quickly compute the effect of VSWR or return loss on transmitted power; cascaded gain and noise figure for up to five amplifier stages; and power-to-voltage conversion. It's the perfect tool to help you solve problems and save time whether you're working in the lab or in the field. Download the app today on GooglePlay for Android or the Apple store for iOS devices.

Mini-Circuits

www.minicircuits.com

XFdtd® EM Simulation Software

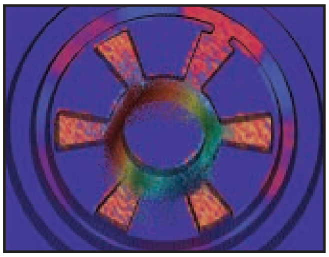


Remcom announced a new capability to import flexible printed circuit board (PCB) designs in the latest update to XFdtd® 3D Electromagnetic Simulation Software. The release includes dielectric volume averaging and several usability conveniences. XFdtd's PCB import dialog also includes the option to wrap a design, such as a flexible circuit, onto a form automatically during the import process. This option conforms the PCB and all of its parts onto the flexible circuit geometry, eliminating the need to bend the model or manually wrap each layer.

Remcom Inc.

www.remcom.com

Electromagnetic Simulation



Tech-X provides electromagnetic simulation software, including Particle-in-Cell (PIC) and Finite Difference Time Domain (FDTD) algorithms featuring tunable conformal geometry using Dey-Mittra cut cells. Tech-X's VSim product simulates helix traveling wave tubes (TWT), magnetrons, klystrons, gyrotrons and other kinetic self-consistent microwave driven plasmas. Other VSim applications include multipactor, metamaterials and photonic devices, such as AWGs (arrayed waveguide gratings) used in silicon photonics. VSim supports massively parallel computing that scales to tens of thousands of processor cores.

Tech-X Corp.

www.txcorp.com

NEW PRODUCTS

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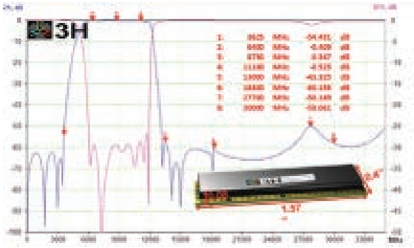
COMPONENTS

C-Band Miniature Filter



3H's new C-Band, bandpass filter offers low insertion loss of <1.0 dB over a passband of 6.4 to 11.1 GHz while providing >50 dB from DC to 3625 MHz and >40 dB @ 13 to 30 GHz. The filter size is 1.57"L × 0.40"W × 0.08"H and meets Mil Std 202 conditions. Contact 3H Communication Systems at (949) 529-1583 or email sales@3hcomm.com.

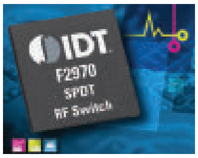
3H Communication Systems
www.3Hcommunicationsystems.com

6-Way Resistive Power Divider

Model 151-215-006 is a resistive 6-way power divider designed for antenna sharing. The 50 Ω units frequency range is DC to 6 GHz. Insertion loss above theoretical loss is + 1 dB nominal DC to 5 GHz and + 1.6 dB nominal 5 to 6 GHz. Input power is 1 W average with an operating temperature of -20°to +100°C. Amplitude tracking is ± 0.5 dB maximum and VSWR is 1.50:1 maximum. The RF connectors are SMA female.

BroadWave Technologies Inc.
www.broadwavetech.com

SPDT Absorptive RF Switch



The IDT® F2970 is a high-linearity 75 Ω broadband switch that supports the DOCSIS 3.1 standard, making it ideal for next-generation cable TV equipment and broadband applications, from the headend to fiber nodes and distribution amplifiers. High linearity across a wide frequency range of 5 to 3000 MHz, features composite triple beat (CTB) and composite second order (CSO) of -90 dBc with 77 & 110 channels with output power of 44 dBmV.

Integrated Device Technology
www.idt.com

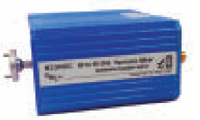
Broadband 1 to 18 GHz Couplers

VENDORVIEW

MECA announced its latest addition to their extensive line of stripline couplers with model 780-dB-9.500-M01, covering from 1 to 18 GHz. Available in 10 and 20 dB models with SMA female connectors, optimized for excellent performance with industry leading specifications offering typical VSWRs ranging from 1.40:1, isolation of 15 dB typical. Made in U.S. and 36-month warranty.

MECA Electronics Inc.
www.e-MECA.com

Portable, Handheld mmWave Solution



OML introduced its new mixer series, Mxx-DxDC that is specifically designed for handheld spectrum analyzers as a portable solution for millimeter wave spectrum analysis measurement. Utilizing the handheld spectrum analyzer generator as an LO source and the built-in DC supply, this harmonic mixer is a portable solution for applications such as Wi-Gig, 5G,E-Band backhaul, collision avoidance radar systems and more in the WR-12, WR-15 and WR-10 bands.

OML Inc.
www.omlinc.com

Waveguide Direct Read Attenuators

VENDORVIEW

Pasternack released a new line of waveguide direct read attenuators for instrumentation, test benches, high efficiency RF/microwave transmissions, satcom, milcom, radar and telecom applications. Pasternack's direct read attenuators are available in WR-42 to WR-10 waveguide standards operating in seven waveguide bands within 18 to 110 GHz. They boast ± 2% typical attenuation accuracy and feature an easy-to-read drum scale and military standard UG-style flanges. Minimum attenuation range is 0 to 50 dB with an insertion loss of 0.5 to 1 dB depending on the frequency range.

Pasternack
www.pasternack.com

Digitally Controlled Analog Phase Shifter

VENDORVIEW

PMI Model No. PS-85M4G-9B-SFF is a 0.085 to 4 GHz, digitally controlled analog phase shifter with capability for phase shifting from 0° to 360°. The unit consists of an analog phase shifter and a digital to analog converter. Nine logic input lines allow 512 discrete values of phase.

Planar Monolithics Industries Inc.
www.pmi-rf.com

Step Phase Shifter

RF-Lambda's 6-bit, 360 step phase shifter features wide band operation with full 1 to 2 GHz bandwidth. High linearity up to 5 W is available upon request. The TTL compatible driver includes fast switching speed, flat phase shifting response and low phase error. It also features low insertion loss, high isolation and a temperature range -40° to +85°C. Customization is available upon request.

RF-Lambda
www.rflambda.com

SP7T and SP8T Switches

RLC Electronics' introduced SP7T and SP8T switches with N connectors. These switches operate up to 6 GHz and are designed for both low power and high power applications (500 W cW at 6 GHz, 2000 W cW at <500 MHz). In addition to long life, the switches also feature extremely low insertion loss (0.1 dB to 4 GHz and 0.3 dB to 6 GHz, typically) and VSWR over the entire frequency range while maintaining high isolation (>80 dB).

RLC Electronics Inc.
www.rlcelectronics.com

Next Generation AEC-Q100 Qualified SPDT Switch

VENDORVIEW

Skyworks unveiled the SKYA21003, a new CMOS silicon-on-insulator (SOI) single pole, double throw (SPDT) switch that is targeted for automotive LTE cellular and general purpose RF applications. This next-generation product is AEC-Q100 grade 2 qualified with

guaranteed RF performance across extended temperature limits, making it an excellent design choice for LTE cellular telematics modems, remote keyless entry devices, infotainment systems, automated toll transponders, garage door openers, GPS/navigation platforms and other wireless control solutions.

Skyworks Solutions Inc.
www.skyworksinc.com

Frequency Converter/Mixer

Serving the 5G and WiGig research efforts, Spacek Labs announced a new frequency converter/mixer, model M60-3X2B. This converter operates in V-Band, with RF input frequencies from 57 to 64 GHz. The LO input frequency is 28.5 to 32 GHz at +15 dBm. Mixer conversion loss is 6 dB typ, 8.5 dB max. An integrated LO X2 multiplier generates the 57 to 64 GHz LO. This mixer assembly can also be used as an up-converter.

Spacek Labs
www.spaceklabs.com

C-Band Circulator

VENDOR**VIEW**

TRAK, a microwave brand of Smiths Interconnect, announced it has added a 4-port, ferrite-based, C-Band circulator to their line of products. Integrating forward and reverse power detectors that operate up to 75 W CW, TRAK offers radar and communications systems designers a unique solution for reducing components and lowering costs while striving to enhance signal clarity. This circulator also features a detection calibration circuit and a high power beryllium oxide (BeO) termination.

TRAK Microwave Corp.
www.TRAK.com

CABLES & CONNECTORS

MMBX Connectors and Adapters

Fairview Microwave Inc. now offers small form factor MMBX connectors and adapters most commonly used on circuit boards and their associated input/output connections for industrial, telecom and consumer product applications. MMBX-style connectors and adapters are specifically designed to provide versatile and easy PCB-to-PCB connections as well as coax-to-PCB connections. Their mechanical design also allows them to work well in backplane applications. These MMBX adapters and connectors from Fairview feature gold-plated beryllium copper contacts and offer a maximum operating frequency of 12.4 GHz.

Fairview Microwave Inc.
www.fairviewmicrowave.com

AMPLIFIERS

Single Band Amplifier

VENDOR**VIEW**

Model 500S1G6 is a 500 W CW solid-state amplifier that has 57 dB gain, delivers 100% rated output power without foldback over the instantaneous 0.7 to 6 GHz band and can survive :1 output VSWR. Applications include radiated susceptibility testing, EW jammers and wireless system and device stress screening tests.

AR RF/Microwave Instrumentation
www.arworld.us

Solid-State Power Amplifier Module

COMTECH PST introduced its latest development for the TWT replacement market covering the full 2000 MHz to 6000 MHz band, providing 100 W in a small, compact, lightweight, ruggedized form factor, ideally suited for UAV, airborne, pods, mobile or surface applications. This SSPA features built in protection and monitoring circuits, low voltage prime power input, high efficiency and reliable solid-state technology. Units can be phase matched for phased array applications. Unit will self-protect under fault conditions and automatically return to normal operation when fault conditions are removed.

COMTECH PST
www.comtechpst.com

Ultra-Broadband High Power Amplifier System

VENDOR**VIEW**

The new AMP2084 ultra-broadband high power amplifier system covers the full 6 to 18 GHz frequency range at 80 W min/100 W typical and features Class AB linear GaN design, gain of 50 dB and less than 4 dB p-p power flatness all in a 5U standard rack chassis. Operating from a 180 to 240 VAC power source, the AMP2084 has built-in protection circuits and is suitable for all single channel modulations standards and for EW, EMI/RFI and high power testing applications.

Exodus Advanced Communications
www.exoduscomm.com

GaN/SiC Transistor

Integra Technologies introduced a new GaN/SiC transistor. Designed for L-Band radar applications, this high-power, GaN-on-SiC HEMT transistor supplies > 380 W of peak pulsed output power at 50 V drain bias, with 20 dB of gain and 54% of efficiency at 150 μs-10% pulse conditions.

Integra Technologies
www.integratech.com

Bidirectional Amplifier

The KU BDA 240250-25 A amplifier covers the 2.45 GHz ISM Band and is designed to support various analog and digital modulation

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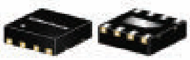
types and signal waveforms. The transmitter features LDMOS technology and delivers more than 20 W P1dB power. The built-in LNA provides a very low noise figure for further enhancement of the receiver's sensitivity. Ultra-fast switching between transmit and receive path is done automatically using lowest delay circuitry. There is also an optional input for external switch control.

Kuhne electronic GmbH
www.kuhne-electronic.de

Monolithic Amplifier

The PMA2-123LN+ is a PHEMT-based wideband, low noise MMIC amplifier with a unique combination of low noise, high IP3, and flat gain over wideband, making it ideal for sensitive, high-dynamic-range receiver applications. This design operates on a single 5 V or 6 V supply, is well matched for 50 Ω and comes in a tiny, low profile package (2 mm × 2 mm, 8 lead MCLP), accommodating dense circuit board layouts.



Mini-Circuits
www.minicircuits.com

100 W GaN Power Amplifier

Richardson RFPD Inc. announced the availability and full design support capabilities for a new X-Band GaN power amplifier from Qorvo. The TGM2635-CP operates from 7.9 to 11 GHz and provides 100 W of saturated output power with 22.5 dB of large signal gain and greater than 35% power-added efficiency. It is offered in a 10-lead 19.05 mm × 19.05 mm bolt-down package with a pure Cu base for superior thermal management. Both RF ports are internally DC-blocked and matched to 50 Ω, allowing for simple system integration.

Richardson RFPD
www.richardsonrfpd.com

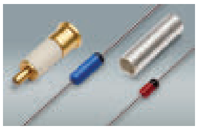
10 W Amplifier Module

The TTRM1074 GaAs amplifier operates at 5000 to 5300 MHz and has a power output of 10 W, while still maintaining a compact form factor of 5.3 × 3.25 × 0.57. This unit also features internal protection against over/under voltage and excessive temperature conditions, which coupled with its rugged construction, ensure fault-free operation in even the most extreme environments.

Triad RF Systems Inc.
www.triadrf.com

SEMICONDUCTORS

Ka-Band Point Contact Mixer Diodes



SemiGen Inc. now offers a series of point contact mixer diodes, the 1N series. The 1N series point contact mixer diodes perform into the Ka-Band. Each device in the series ideally designed with noise figures as low as 5.5 dB at 3.06 GHz and 6 dB at 9.375 GHz. With VSWRs of 1.3:1 and impedances ranging from 200 to 600 Ω, these devices can serve as drop in replacements for all military and commercial requirements.

SemiGen Inc.
www.semigen.net

SOURCES

Oven Controlled Oscillator

The new YH1421 oven controlled oscillator is available from 10 to 120 MHz, with a +3 dBm typical sinewave output into 50 Ω. The YH1421 features low phase noise with a -160 dBc/Hz noise floor, and also maintains very good hold-over and medium/long term stability for wireless communications and data, including 5G. The YH1421 uses a +5 or +3.3 VDC supply and is packaged in a compact 0.8" × 0.5", low profile, DIP package. It can also be provided with an SMT adapter.

Greenray Industries Inc.
www.greenrayindustries.com

Programmable Synthesizer

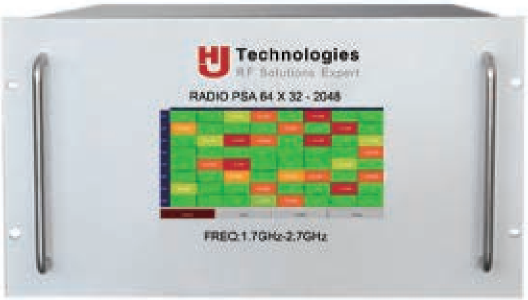
The KMTS2500-110250-10 is a programmable synthesizer covering greater-than an octave bandwidth from 1.1 to 2.5 GHz with a 1 Hz resolution. This synthesizer features an on-board micro-controller that allows for self-programmable fixed frequency or wideband signal generation, useful for testing global navigation satellite system products. This model features excellent phase noise performance of 95 dBc/Hz at 10 kHz offset and 110 dBc/Hz at 100 kHz offset when used with a low noise, external 10 MHz frequency reference.

Synergy Microwave Corp.
www.synergymwave.com

ANTENNAS

Ceramic Patch Antennas

RFMW Ltd. announced design and sales support for API Technologies' ceramic patch antennas. Model PA25-1621-025SALF offers 4 dBiC of gain at a center frequency of 1621 MHz ± 4 MHz. 10 dB bandwidth is 25 MHz. API Technologies offers a wide range of



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Acceptance Notification:
July 5, 2017

Full Paper Submission:
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RFMW Ltd.
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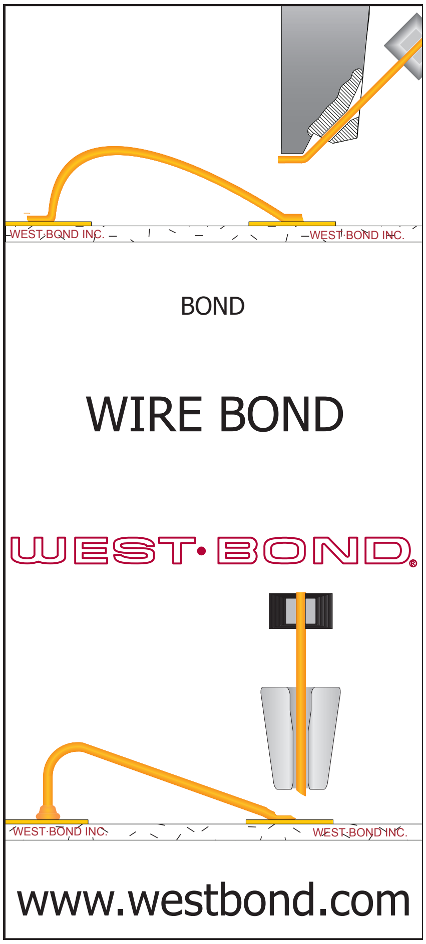


Ka-Band Omnidirectional Antenna

Model SAO-2832930610-28-S1 is a WR-28 omnidirectional antenna that operates between 28 and 29 GHz. This vertically polarized antenna offers 360° azimuth coverage with 6 dB gain and ±3 dB gain flatness. The antenna features a half power beamwidth of 10° in the vertical direction. The actual operating frequency of this omnidirectional antenna is much broader.

SAGE Millimeter
www.sagemillimeter.com

MIMO Sector Antennas

Three new MIMO sector antennas from Southwest Antennas are available in 1.4 to 1.7 GHz or 1.7 to 2.5 GHz frequency options for international applications, U.S. Federal Law Enforcement or license-free ISM Band use, and are compatible with a wide variety of multi-port MIMO radio systems currently on the market. The focused sectorial radiation pattern is ideal for directional communication. Slant left/right and vertical polarization provide superior MIMO polarization and spatial diversity for crowded RF environments.

Southwest Antennas
www.southwestantennas.com

TEST & MEASUREMENT

Real-Time Spectrum Analyzer

Berkeley Nucleonics customers made a wish list for the RTSA7500 series real-time spectrum analyzer and BNC listened. Introducing the newly launched RTSA7550 solution. With a dramatically faster sweeping speed of 28 GHz/sec at 10 kHz resolution bandwidth, a 10× increase in streaming rate, now 360 Mbit/sec to enable real-time demodulation, a starting frequency of 9 kHz, and a real-time bandwidth of up to 160 MHz, the RTSA7550 has now become the standard for price-performance comparisons.

Berkeley Nucleonics
www.berkeleynucleonics.com

Low Noise Power Supply

This power supply is an ultra-clean linear DC voltage source designed specifically for testing noise sensitive components. Noise on the output of the supply is well under one nanovolt per root Hz, and is significantly quieter than any available laboratory DC voltage supply. The power supply can also operate in constant current mode with exceptionally low current noise. It is ideal for providing bias to low noise oscillators, amplifiers and phase locked loop circuits. It is quiet enough to drive the tune lines of VCOs, VCXOs and YIG devices.

Black Box Instruments
blackboxinst.com

Reverberation Chamber

The RTS25 is the most compact member of Bluetest's Reverberation Test System (RTS) family. It is optimized for measurements on the 2.4 and 5 GHz ISM Bands and is therefore suitable for Over-the-Air (OTA) measurements of WLAN, Bluetooth devices, or IoT applications such as ZigBee and Thread. The RTS25 enables a shielded, controlled and repeatable OTA environment. The reverberation chamber provides an inherent 3D multipath environment that is needed to enable MIMO functionality.

Bluetest AB
www.bluetest.se

8 GHz RFeye® Desktop

CRFS, a leader in real-time RF spectrum monitoring solutions, unveils its next generation 8 GHz RFeye® Desktop. The RFeye Desktop is the first commercially available, high performance spectrum analyzer which is truly portable—it fits in the palm of your hand and can be carried around in your laptop bag. The RFeye Desktop looks nothing like a traditional piece of test and measurement equipment. It is presented in a compact, lightweight, ergonomic package just like in a consumer electronics product.

CRFS Ltd.
www.crfs.com

Bolt-on V- and E-Band Test Modules

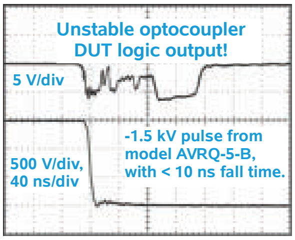
Millitech, a microwave brand of Smiths Interconnect, announced the release of a series of bolt-on V- and E-Band test modules that enhance the frequency range of a user's vector network analyzer to V-Band (69 GHz) or E-Band (90 GHz). These budget conscious modules can save thousands in custom millimeter wave test set design and development costs, as this minimalized frequency extension via the standard SMA test connection. Spartan Test Modules™ offer built in detectors and are also compatible with scalar network analyzers.

Millitech
www.millitech.com

Arbitrary Waveform Generator

RIGOL Technologies Inc. announced an expansion of their waveform generator portfolio. The new DG1022Z gives budget constrained customers an uncompromised solution with advanced features typically reserved for much higher price points. Now makers, educators, and IoT designers working with both electrical and RF applications can build long complex arbitrary waves, generate 8th order harmonics, create advanced modulations and inject random noise.

RIGOL Technologies Inc.
www.rigolna.com


Unstable optocoupler
DUT logic output!
5 V/div
-1.5 kV pulse from
model AVRQ-5-B,
with < 10 ns fall time.
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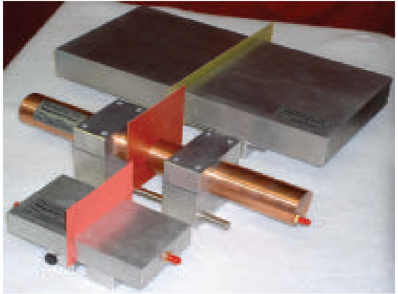
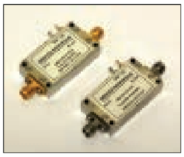
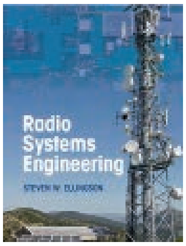
40 ns/div







Radio Systems Engineering

Steven W. Ellingson

Steven Ellingson has attempted to write a comprehensive technical explanation of radio. He begins with λf = c, builds the system concepts (propagation, noise, modulation, link analysis, receivers, transmitters), then delves into the functional components that embody radio systems (antennas, amplifiers, filters and mutliplexers, mixers, frequency synthesizers). He concludes the discussion with an appendix that describes the characteristics of common radio systems, from broadcasting to remote keyless entry (RKE) — of course, cellular, Wi-Fi, Bluetooth and ZigBee are included. Using the parlance of the Open System Interconnection (OSI) model, he only treats the physical layer of the network, and it only takes him some 600 pages.

Ironically, despite his goal to be comprehensive, Ellingson intentionally avoids discussing the Smith chart: "I feel the value of knowing how to maneuver the circles, arcs and rotations of the Smith chart is not really apparent until one is comfortable with the fundamentals of RF circuit analysis and design."

Ellingson is an associate professor at Virginia Tech, and the book was, no doubt, born from his teaching. He intends it to serve either as the primary textbook for senior or graduate classes or as a supplementary text for a specialized graduate-level course. Each chapter concludes with problems to test students' understanding. Despite the textbook focus, the book is equally useful as a reference for the practicing engineer, one seeking to refresh knowledge or gain insight in a new technical area. To that end, this is one of the books crossing my desk that I will keep on my bookshelf.

To order the book:

Published by Cambridge University Press
www.cambridge.org
ISBN-13: 978-1-107-06828-5
650 pages
$94.99, Hardback
$76.00, Adobe eBook

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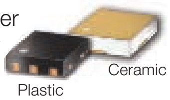
Ceramic
Plastic

FABS and LABS

Quietly Gaining Share with Smart Silicon

The technology wall separating GaAs and silicon keeps moving higher in frequency. Integrated Device Technology (IDT) is one of the companies pushing silicon forward, happily winning designs and taking market share from GaAs. Not as well known as some of the larger silicon IC players, IDT was formed in 1980 and has grown to more than $740 million in annual revenue (adding the prior four quarters). The company's manufacturing strategy uses external foundries to fabricate CMOS, SiGe and SOI ICs, which are tested in IDT's own manufacturing facility in Penang, Malaysia.

IDT quietly entered the RF space in 2009, without a history in either RF or GaAs. The move was based on the confidence that IDT could grow a business through product innovation, not acquisition. That strategy, which it calls "smart silicon," has proven successful, reflected by the growth of the RF team, now with two design centers in Boston and San Diego, and the rapid expansion of IDT's RF business revenue. Its RF product portfolio — all silicon — is focused below 6 GHz and includes virtually all the small-signal RF and IF circuit functions used in a wireless base station: switches, amplifiers, variable-gain amplifiers (VGA), digital-step and voltage variable attenuators (DSA and VVA), mixers, modulators, demodulators, phase-locked loops and synthesizers. IDT also offers products for CATV networks, which are matched to 75 Ω.

Back to smart silicon. What makes these products smart and so attractive to customers? In general, silicon has lower power consumption, better reliability and a wider operating temperature range than GaAs. To these, IDT's RF designers have added unique and patented circuit techniques to differentiate their products. IDT's switches and DSAs are designed to change states without high transients or glitches (Glitch-Free™), and port impedances remain constant during the transition ($K_{|Z|}$). VGAs maintain a constant noise figure as the gain is reduced (FlatNoise™), and the output intercept point remains high and constant as the gain changes (K_{LIN}). Mixers incorporate a technology to minimize intermodulation products (Zero-Distortion™).

Consumer demand for data is driving the wireless industry to 5G, what Qualcomm's CEO has likened to the introduction of electricity and the automobile. For the operators and network equipment manufacturers, it means more, smaller cells, each one with multiple inputs and multiple outputs (MIMO). For the semiconductor supplier, it means integration — which plays to another of IDT's strengths. What you won't see in IDT's online catalog are the many additional integrated products that combine individual circuit functions into custom assemblies for next-generation systems. IDT's product development process is rigorous in definition, yet quick in execution, to minimize time-to-market and deliver well-integrated solutions. All new designs are run on production masks. Circuit changes are made with the metal layers, enabling iterations to be processed in four weeks rather than the normal 10 to 12 weeks for an end-to-end silicon process.

IDT's mantra is innovation, which is the only sane strategy to enter a crowded and price sensitive market. The RF team's performance has established IDT's credentials, shipping millions of ICs per month to four of the top five base station manufacturers. Combining smart silicon, integration and customer credibility, IDT is well positioned to be a leading IC supplier for 5G infrastructure, even at millimeter wave frequencies.

www.idt.com/products/rf-products

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- Lowest Loss
- Custom Designs Available

Combiners / Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Insertion Loss (dB)	VSWR	Connectors (Sum Port, Inputs/Outputs)
D8182	5-Way	1175-1375	1,500	0.4	1.35:1	1 5/8″ EIA, N Female
D8454	8-Way	370-450	10,000	0.25	1.30:1	3 1/8″ EIA, N Female
D9710	8-Way	1000-2500	2,000	0.3	1.40:1	1 5/8″ EIA, N Female
D9529	8-Way	2305-2360	1,000	0.2	1.15:1	7/16 Female, N Female
D9528	8-Way	2305-2360	2,000	0.2	1.15:1	7/8″ EIA, N Female
D5320	12-Way	470-860	500	0.3	1.30:1	All N Female
D9194	16-Way	2305-2360	1,000	0.2	1.15:1	7/16 Female, SMA Female
D9527	16-Way	2305-2360	2,000	0.2	1.15:1	7/8″ EIA, N Female
D9706	16-Way	2700-3500	6,000	0.35	1.35:1	Waveguide, N Female
D6857	32-Way	1200-1400	4,000	0.5	1.35:1	1 5/8″ EIA, TNC Female

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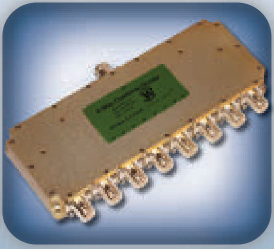
Directional Couplers



0° Combiners/Dividers

90° Hybrid Couplers

180° Hybrid Combiners

Absorptive Filters